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TSAGI Central Aerohydrodynamic Institute

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INVESTIGATION OF CONTROLLABILITY CRITERIA OF UNMANOEUVERABLE AIRCRAFT EQUIPPED WITH A SIDE STICK

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ABSTRACT

The work is done at TsAGI in complience with the contract SPC—93—4046.

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CONTENTS

INTRODUCTION

Controllability criterion development has always been attributed much attention, since they affect in an essential way aircraft handling qualities, effectiveness and flight safety.Together with the development of aviation the controllability criteria are constantly developing. Today's aviation with widely automated manual control loop requires development of generalized criteria, which provide controlability estimation for different piloting tasks for aircraft with different, including non—conventional dynamic characteristics and control levers [1 — 9].

At present, the most developed are controllability criteria for estimation of aircraft required dynamic characteristics. Somewhat less developed are the criteria for estimation of control lever loading and controllability characteristic optimum values. These characteristics not only depend in a complicated way one on another, but also on flight regime, dynamic characteristics, aircraft and control lever type. There is no sufficiently general criterion for estimating control lever loading and control sensitivity characteristic optimum values in literature. This consideration not only hampers the mentioned characteristics optimization when creating an aircraft, but also restrains essentially the controllability theory as a whole. Development of such criteria has become especially important in connection with new control lever equipped aircraft development (side stick, miniwheel).

One of the main problems of the report is further development of the theoretical approach, proposed earlier [7,8,9], to the controllability criteria for control lever loading and control sensitivity characteristics optimization, taking into account their mutual influence depending on aircraft dynamic characteristics and flight regimes.

Another problem of the report is specification of the mentioned criteria as applied to non—manoeuverable aircraft with side control stick and analysis of such aircraft controlability features.

The principal possibility and expediency of the side control stick application on remotely controlled aircraft has been already proved in practice. At present it is being used on different aircraft: for instance on F—16, "Rafale", YF—22, fighters, on the latest reentry vehicles of the Space Shuttle series, on passenger aircraft A—320, A—340.

Side control stick has a number of advantages in comparison with the conventional control levers: it allows one to free the room in front of the pilot and improve the instrument panel view, yields a certain gain in the control system weight, creates more comfortable conditions for a pilot, in particular for taking and leaving the working place, and also possesses some other advantages. These side control stick properties are evident and well known. More complex and less studied still are the handling qualities of aircraft equipped with the side control stick and controllability characteristic optimization for such aircraft. The lack of side control stick equipped aircraft creation experience and a limited number of publications require that the available data be systematized and investigations in these area be conducted.

In order to solve the formulated problems, in the present report the authors analyzed the literature data, conducted flight simulator experiments, performed generalization of the available and obtained data, carried out theoretical investigation, and compared the obtained data with the flight tests results and the data on specific aircraft.

The experimental investigations of side control stick equipped non—maneuverable aircraft controlability were carried out on TsAGI'S flight simulators FS—102 and FS—101. The experimental results are compared with the data available and with results, obtained on the flying laboratory TU—154M with authors participation. Different pilots took part in the experiments, including test pilots.

1. EXPERIMENTAL CONDITIONS

1.1. Flight simulator

The majority of experiments were carried out on TsAGI's FS–102 flight simulator (Fig.1.1). This facility is designed to study stability and controllability of unmanoeuverable aircraft. Its characteristics are:

Pilot cockpit:

Two seats, with furniture and regular instrumentation, corresponding to the nonmanoeuverable aircraft.

Control levers:

Changeable, including electro–hydraulic loading system (central stick, wheel, side stick, pedals).

Visual system:

One channel with optical collimator and analog–digital synthesis of a runway and Earth surface colour picture (Fig.1.2).

Cockpit motion system:

6–degrees of freedom, synergetic type with maximum displacements in altitude ±1.2 m; in longitudinal and lateral directions ±1.5 m; in roll ±30 deg; in pitch ±40 deg; in yaw ±60 deg.

1.2. The investigated side control stick

In experiments we used two types of side control sticks. One of them is RUS–D1 side control stick with hydraulic damper and changeable loading springs. This side control stick was also used in the flight investigations on the flying laboratory TU–154M, which made the comparison of the simulator tests data with the real flight ones much more groundful. At the same time in simulator tests another side control stick was used – with a universal electro–hydraulic loading system, allowing to reproduce practically arbitrary loading variation laws.

The RUS–D1 side control stick (Fig.1.3) – 3-DOF, provides forces, necessary for control and electric signal generation in pitch, yaw and roll. For all the control channels, the side control stick has displacement transducers, there are also force transducers in pitch and roll, which provide control signals, proportional to both stick displacements and forces on it.

Fig.1.4 shows the side control stick constructive layout. The control stick includes a handle (1), moving inside the case, owing to the 3–DOF cardan unit (3), spring loaders (29, 34, 39) – pitch, roll and yaw accordingly, reserved displacement transducers in pitch (31–33), roll (35–37) and yaw (40–42), 2–DOF force transducer (9), hydraulic dampers in pitch (30) and roll (35). Each damper has adjustment bolts, providing the load damping coefficient wide range of variation. The stick is equipped with additional loaders set with variable stiffness changeable

springs, whose design allows one to vary, along with the load gradient, also the breakout force value.

The RUS–D1 design allows to vary its kinematic, dynamic and loading characteristics (displacement X, forces F, loading gradient F^x , damping $F^{\dot{x}}$, breakout force value F_0, etc.).

Main technical characteristics of the RUS–D1 side control stick:

1. Maximum deflectons of the side control stick in pitch, roll and yaw are ±20° with smooth limitation adjustment within the whole range 0±20°.
2. The side control stick arm (the distance between its center and the rotation axis) in pitch and roll is 120 mm.
3. The maximum force on the stick (measured in its center)

   in pitch and roll is 2 – 12 kg;

   in yaw 0.08 – 0.3 kg
4. The breakout force value F

   in pitch and roll 0 – 1 kg;

   in yaw 0.01 – 0.04 kg
5. Friction, measured in the stick center does not exceed

   in pitch and roll 0.2 kg;

   in yaw 0.005 kg
6. Load damping coefficient in pitch and roll is varied within range 0 – 0.01 kg/mm/s.
7. The displacement transducers (three times reserved), of induction type, voltage supply ~36 Volt, 400 Hz.
8. The force transducers in pitch and roll are four times reserved.
9. Dimensions : 80×80×365 mm.
10. Weight does not exceed 2.9 kg.

The RUS–D1 side control stick was developed jointly by NIIAO and TsAGI. It was widely utilized in flight simulation experiments at TsAGI and flight experiments on Ka–32 helicoper and TU–154M in–flight simulator. It gained good reputation as a universal research instrument. In this work it was used in its 2-DOF option when studying the side control stick influence upon aircraft controllability.

Fig.1.5 shows a picture of the side control stick with electro–hydraulic loading system, used in the experiments. The side stick has been developed at TsAGI. It consists of a handle 1, force transduser (in pitch and roll) 2, 2-DOF cardan unit 3, electro–hydraulic loading drives 4 and 5, displacement transdusers 6 and 7 in pitch and roll correspondingly, control unit with the loading laws computation.

Typical loading characteristics and varied loading parameter ranges in the both channels are given in Fig.1.6.

1.3. Simulated aircraft dynamics, flight regimes and varied parameters

Simulated were a landing approach (V=260 km/h), cruise flight (H=11 km, M=0.8) and turn–level flight (H=400 m, V=400 km/h).

Usually, when studying general problems of aircraft controlability, e.g. in MIL–8785 case, aircraft motion equations are considered linearized with respect to a horizontal flight with a constant velocity. Such equations were used in the present report as it is of general type. In the investigations the authors considered generalized stability and controllability characteristics ($\omega_{sp}, \varsigma, \ldots$). In connection with this the motion equation parameters were expressed via these characteristics. These equations can be represented in the following form (long periodic motion component was neglected):

$$
\begin{aligned}
&\dot{\alpha} = -\frac{g}{V} n_{z_\alpha}(\alpha + \alpha_w) + q \\
&\dot{q} = -\left[\omega_{sp}^2 + \frac{g}{V} n_{z_\alpha}\left(\frac{g}{V} n_{z_\alpha} - 2\varsigma_{sp}\omega_{sp}\right)\right](\alpha + \alpha_w) + \\
&\quad + \left(\frac{g}{V} n_{z_\alpha} - 2\varsigma_{sp}\omega_{sp}\right) q + K_e \overline{M}_{\delta_e} x_e (t - \tau_e) \\
&\dot{\theta} = q; \quad \gamma = \theta - \alpha; \\
&\dot{H} = -W = V_0 \gamma; \\
&\dot{X} = V_0 \\
&\ddot{\beta} + 2\varsigma_r \omega_r \dot{\beta} + \omega_r^2 \beta = K_r \overline{N}_{\delta_r} x_r (t - \tau_r) + \frac{g}{V} n_{y_\beta} \dot{\beta}_w - \omega_r^2 \beta_w \\
&\dot{p} + \frac{1}{\tau_1} p = K_a \overline{L}_{\delta_a} x_1 (t - \tau_a) - \overline{L}_\beta (\beta + \beta_w) \\
&\dot{\phi} = p \\
&-\dot{\psi} = -\dot{\beta} - \frac{g}{V} n_{y_\beta} - \frac{g}{V}\phi \\
&\dot{Y} = V_0(-\beta + \psi)
\end{aligned}
\tag{1.1}
$$

where $\alpha, \theta, \gamma, n_z, H, X$ – are correspondingly the increments of angles of attack, pitch, flight path angle, normal g–load, flying altitude and range with respect to their initial values $\alpha = \alpha_0, \theta_0 = \alpha_0, \gamma_0 = 0, n_{z_0} = 1, H_0, X_0$; β, ϕ, ψ, Y – are the increments of sideslip, roll, yaw angles and lateral displacement corresponding to the initial values $\beta_0 = \phi_0 = \psi_0 = Y_0 = 0$; $K_e \overline{M}_{\delta_e} x_e, K_r \overline{N}_{\delta_r} x_r, K_a \overline{L}_{\delta_a} x_a$ – are the initial pitch, roll and yaw rates per unit displacement of a corresponding control lever (side control stick and pedals); τ_e, τ_r, τ_a – are the equivalent time delay in control loops, approximated by the first term of the Pade series expansion:

$$
e^{-s\tau} = \frac{1 - s\frac{\tau}{2}}{1 + s\frac{\tau}{2}}
$$

where α_w, β_w – are the angle of attack and sideslip angle caused by the wind disturbances.

The following aircraft characteristics were varied in the experiments:

- dynamic characteristics of longitudinal and roll motion
  - natural frequency ω_{sp} and relative damping ς_{sp} of a longitudinal short periodic motion;
  - parameter n_{z_α};
  - pitch τ_e and roll τ_a channels control system time lag;
  - isolated roll motion time constant τ_1.
- the longitudinal and lateral aircraft control sensitivity characteristics $X_{n_z}, F_{n_z}, X_p, F_p$
- the side control stick loading characteristics in the longitudinal and lateral control channels
  - loading gradients F_e^x, F_a^x;
  - breakout force F_{0_e}, F_{0_a};
  - damping coefficients $F_e^{\dot{x}}, F_a^{\dot{x}}$.

The dynamic characteristics of yaw motion and directional aircraft controllability were held constant. Coefficient values in the motion equations (1), determining directional aircraft controllability characteristics, were taken to be :

$$K_r \cdot \overline{N}_{\delta_r} = -8 \ {}^{1}\!/_{ms^2}; \quad \omega_r = 1.64\ s^{-1}; \quad \varsigma_r = 0.3; \quad F_r^x = 0.4\ {}^{kg}\!/_{mm}; \quad \overline{L}_\beta = -6.47\ s^{-2}$$

Derivative X_{n_z} and X_p variation (and hence F_{n_z} and F_p) is accomplished by variation of the coefficient of transmission from the control lever to the longitudinal and lateral controls K_e and K_a.

In order to reveal the peculiarities of the side control sticks from the controllability point of view, a comparative study of aircraft controllability by means of the side control stick and the conventional control levers — a central control stick and a wheel, has been conducted.

The mentioned flight regimes piloting aimed at performing typical maneuvers on a heavy subsonic non–manoeuverable aircraft. The pilot was asked to estimate the described aircraft handling qualities. The handling qualities were ranked by the pilot according to the 10–grade Cooper–Harper type scale.

Three pilots took part in the experiments. One of them, a test pilot participated both in simulator and flight experiments on the TU–154M flying laboratory. The two others – pilots in the past, are skilled and experienced in flight simulation experiments of various programmes. Pilot – operators took part in certain experiments.

For the analysis of the experimental results the motion parameter variations were recordered and the handling precision was estimated.

After each flight the pilots remarked on the piloting features and handling characteristics according to the Cooper-Harper type scale. To obtain the outcome estimation for certain experiments with a huge data flow, the obtained handling estimates were processed according to the special technique earlier developed at TsAGI [11].

In certain experiments the quantitative data on piloting were found: spectral density, RMS piloting errors and pilot frequency characteristics.

2. SIDE STICK AIRCRAFT CONTROLLABILITY FEATURES

2.1. Side stick controllability versus conventional control levers

As it was previously noted, at present there is no doubt about the principal possibility of the side stick utilization for aircraft of different types control, however due to the lack of experience its utilization in the aircraft control systems, the ultimate perception of differences in side stick and other control levers equipped aircraft controlability restrains to a great extent the utilization of the side control sticks on aircraft. Let us consider these differences for every control channel.

Practice of the side control stick utilization on different aircraft, the available literature data [13], [14], [15] show, that for different aircraft, utilizing side control sticks in standard flight conditions one can provide piloting characteristics and control precision in the longitudinal channel not worse than in the case of the conventional control levers. An overwhelming majority of pilots prefer control by means of side control sticks. At the same time there is no final decision on the differences in aircraft controlability with side control sticks and with the conventional control levers.

The investigations carried out in the present work show, that the side control stick provides even better piloting quality in the longitudinal control channel and somewhat worse in the lateral control channel in comparison with central sticks and control wheels.

Fig.2.1–2.3 show data for the longitudinal control channel. Fig.2.1 gives an aerospace vehicle piloting processes at the landing stage both with the side and central control sticks, performed on the FS–102 flight simulator. It is seen, that the side stick permits smooth variation of the vertical velocity V_y when flaring, to follow the required for flaring g–load and angle of attack variation with smaller oscillation amplitude and more precisely.

Fig.2.2 and 2.3 give piloting estimates PR as functions of the static stability and the dampening coefficient of a non–maneuver airplane longitudinal short–periodic motion with a wheel and side stick–equipped. The experimental data show, that the side control stick is considerably preferable in comparison with the conventional control levers in the longitudinal control channel in the case of a small stability margin and small longitudinal motion dampening.

This piloting quality improvement in the longitudinal channel can be explained with the help of the pilot dynamic characteristics identification experimental results, obtained in the problem of the pitch angle stabilization (Fig.2.4). It is seen, the pilot control lag τ decreases when he operates by means of the side stick. The lag decrease accounts for a less side stick time delay and higher dynamic properties of the muscles, involved in the motion when using the side stick in the longitudinal channel. As a result the overall pilot reaction time improves, his gain coefficient and the open system "aircraft–pilot" stability margin grow. This enables the pilot to provide the "aircraft–pilot" system stability even at less stability margins and an airplane dampening. The conclusion was surely approved by experiments.

The peculiarities of the side stick–equipped non–maneuver aircraft lateral controlability were estimated by the comparative analysis of central stick and wheel control processes (Fig.2.5).

The data show, that the side control stick provides a worse control precision in the lateral channel both at good ($\tau_l = 1$s) and bad ($\tau_l = 10$ s) airplane roll dynamic

characteristics, than the wheel. Evidently, the difference in the "arm—control lever" system dynamic features for the wheel and the side stick is not so considerable in the lateral control channel in comparison with the longitudinal one. Secondly, pilots can more accurate measure out the roll control efforts by means of the wheel, when the both arms are operating, rather than with one arm by means of the side control stick. It should be taken into account, that pilots expressed higher roll oscillations in the case of the side stick, especially when the latter had no damper.

As far as the central stick is concerned, the presented data show, that the side stick provides better piloting precision at worse aircraft dynamic characteristics. This accounts, most probably, for the central stick higher time delay.

Pilots noticed for both longitudinal and lateral control channels a less pilot accident actions anticountermeasures and more considerable interaction of the longitudinal and lateral control. Even in the standard piloting conditions there was an interference, caused by the side stick controls, and roll disturbances at the intensive control in the longitudinal channel. The mentioned side stick drawbacks may well became dangerous in the emergency situations when pilots roughly operate. The conventional control levers seem more expedient in the emergency situations, because they require higher efforts and displacements and involve different muscles and sensors, giving the pilot distinct kinesthetic information on the control levers actions. This item should be paid a particular attention to further.

Thus, the side control stick from the non—maneuver airplane controlability point of view turns out to be more advisable in some respects, and worse than the control wheel in the others. Hence, the side stick application must be estimated separately for each case and considering specific conditions.

2.2. The ergonomic estimation of side control stick}

Side control sticks of the lever type are usually used on airplanes. In this case the pitch and roll—rotate axes cross in a point, located below the stick handle (Fig.1.3). That are the side control sticks used on A—320, A—340 airplanes.

As it has been already said a feature of these side control sticks is an mutual influence of the pitch and roll forces, because one and the same arm links produce roll and pitch control forces. It causes difficulties when measuring out the forces in doses. They say that in this case the stick rotate kinematic axes disagree with the physiological arm axes. All side control sticks of the lever type are notable for the drawback, including the conventional control stick, used both for maneuver and non—maneuver airplanes. The wheel lacks the drawback because its pitch and roll—rotate axes are kinematically parted and control forces are accordingly separated: one muscle group contract enables roll motion, the forearm displacement enables pitch motion.

The mentioned mutual influence is particularly characteristic of the roll channel, especially when there are some balancing forces in the pitch channel. When flying on fast maneuver airplanes, pilots easily notice and correct the unforeseen roll component of involuntary hindrance, moving the stick. For non—maneuver airplanes which are not so fast the roll deflection presents a danger especially at landing and taking—off, because pilots notice and eliminate it much more slowly. That is why it is so necessary to take actions to remove the drawback.

One of the actions is such a construction of the side control stick that provides the "physiological separation" of control forces, e.g. by means of the divided pitch and roll—rotate axes. Fig.2.6 shows two possible options of this side control stick construction. In the first case the pitch—rotate axis is located below the stick handle and the roll—rotate axis — on the level of the stick arm middle and directed along the forearm.

In the second case (so—called "lock—type" side stick) the advance control motion in the pitch channel is put into effect together with the elbow—rest. There is no information about the advantages of this option in comparison with the others in literature. More than that, surely a moving elbow—rest causes a loss of measuring out precision, because of the lack of the tactile information on the arm displacement. Vice versa in the case of the fixed elbow—rest the tactile information considerably increases the motion precision.

The other type of the side control stick with the pitch and roll "physiological separation" is hand—type side control stick, where axes of rotation cross either in the hand center or in the wrist. This one conforms to the physiology of the human arm best of all, because in this case different groups of muscles provide precise control forces in the both channels. Pilots appreciated this type of side control stick, but due to the sophisticated construction, manufacture and maintenance technology it was not put into production. At present an original construction of the hand type side stick has been developed. This option of side control stick is expedient to be studied in detail.

One of the principal problems when developing a control system with a side stick is the type and amount of control effort components, realized by the side control stick. An overwhelming majority of the side sticks used earlier and now are of two components, for the pitch and roll control, both moving side control sticks with the displacement steering signals (A—320) and fixed ones with the force steering signals (F—16). Sometimes the latter side sticks are used in the moving option on an elastic (spring or rubber) foundation.

There are three component side control sticks at present to control the yaw channel. Some results of such side sticks investigation and conclusions on their utilization have already been mentioned.

The side control stick displacement range, effort value and the type of loading are the most important characteristics, that determine the side control stick construction, influence the controlability characteristics and the control system as a whole.

The hand mobility determine the range of the side stick maximum deflections. For the pitch control, performed by turning a hand in the palm plane, the advisable stick deflection angle is ±20°. The advance displacement range is determined via the stick arm. Taking into account the limited arm dimensions the stick arm is expedient to be rather small. Thus, if a side control stick has the deflection angle ±20° and the stick arm (measured through the lever center) is 120 mm, then the stick total displacement is ±40 mm (A–320 has ±35 mm total displacement at the deflection angle ±16°).

For the roll control, performed by rotating an arm with respect to the forearm axis, much more considerable stick deflection angle is permissible, but due to constructive reasons it is usually taken 20°–30°.

As far as the effort value is concerned, it is known that there is a certain effort–control lever displacement relation. The relation is complex, depends on the control lever type and various factors. The problem has been studied in detail in the presented work and we will dwell upon it below.

There are two ways to form the control lever loading laws, providing acceptable handling qualities. The first one, conventional for the maneuver aircraft, includes the loading characteristic break, corresponding to the force gradient decrease at high deflections of the control stick.

The second way implies the side stick loading break, corresponding to the force gradient growth at high deflections of the control stick. The latter law of the side stick loading works on A–320 airplane in the longitudinal control channel (Fig.2.7). Most probably it was done in order to improve the precision of the side stick displacement measuring out, and hence, the controlability precision at the expense of the effort increment growth at high deflections of the side stick.

The two opposite approaches account for the lack of a steady opinion on the problem. It should be studied in future.

Fig.2.7 give as well the side control stick roll loading characteristics for the A–320 airplane. One can see that roll loading is asymmetric in order to balance human "asymmetry" in perceiving forces, applied to the side stick to the right or to the left. The chosen loading parameter values, as it will be shown below, conform to the results of the authors' investigation.

In conclusion we will consider some ergonomic problems and the side stick location in the cockpit.

At present a lever similar to the central stick lever is common. But the side stick lever has a greater top rake. These side sticks are habitual, tested in flight on many types of airplanes and do not incur the pilots blame. There is some experience in using side sticks with a lever, enfolded by the hand. This lever seems to conform to the arm physiology to a greater extent. However, this changes the arrangement of additional controls on the lever, and hence, the way pilots used to operate. That is why this type of the side stick was not widely spread. But optimization of the lever shape in order to find the most comfortable option and provide a better piloting accuracy is to be continued.

Side control sticks are higher estimated by pilots from the ergonomic point of view in comparison with the conventional control levers. In their opinion a side control stick with a properly fixed elbow−rests provides a more comfortable working position of the pilot in comparison with central sticks and wheels.

The side stick setting dimensions determine its location in the cockpit, for example in the "Buran" cockpit (the dimensions are measured with respect to the lever center) :

– the distance from the seat longitudinal plane is 280 mm
– the seat height with respect to the S−point is 280 mm
– the distance from the S−point along the longitudinal axis X= 320±40 mm
– lever setting angle in the longitudinal plane is 30° − 40°
– the side control stick roll setting angle is 12° − 18°

2.3. Estimation of aircraft left hand control. Two side sticks interaction.

As it is known for non–maneuver aircraft, equipped with a side control stick and piloting by two pilots, the most common is a configuration where one of the pilots (the right one) uses the right side control stick, while the left pilot operates the left side control stick. Thus, the problem of left–hand controlability arises (the statistics shows that left–handed persons are 10%, right–handed – are 60%, and ambidextrous persons are 30%).

The possibility of left hand piloting in regular flight conditions is already practically confirmed by utilization of the left hand side control stick on the A–320 passenger airplane. Nevertheless, valid is the principal issue of how much the left hand piloting differs from the right hand one, as well as of how accurate and reliable the left hand piloting proves to be in emergency situations.

The authors carried out special simulation experiments to determine piloting precision and maximum permissible dynamic characteristics of the controlled object, allowing both right and left hand piloting. These experiments showed that skilled pilots, who always have some experience in left hand piloting (e.g. when the right hand is involved in other activities) usually after 2–3 training flights achieved the required accuracy of piloting though it was somewhat less than with the right side control stick.

Left hand control training has been studied as well. Operators, skilled in the right hand controlling, but unexperienced in the left hand one, quickly gained the skills. Fig.2.8 shows the results of the experiments. After 2–3 days of training the operator hand managed the piloting task. However the left hand piloting precision was considerably lower, than the right hand one, that may well impair flight safety, especially at adverse flight conditions and failure situations. That is why we see fit to escape the aircraft cockpit arrangement when a standard side control stick is on the left of a pilot.

An emergency situation when a pilot has to handle a right side control stick with his left hand may happen. Experiments have shown the principal possibility of the control with worse qualities, but on this purpose a reserve left side control stick is advisable.

For the twin–pilot aircraft when using the side control sticks, mechanically independent one from another, one needs to solve the problem of the pilots simultaneous or consecutive control interaction.

On A–320 airplanes, the twin pilot interaction problem when controlling is solved by processing signals coming from the left and right side control sticks. In [16] investigated were also other techniques of the pilots interaction problems, including due to the mechanical link between side control sticks. The results of the investigation are given in fig.2.8 as pilots estimates PR according to the link option preferability. These results show, that up to now there are no side control stick link options, superior to to the mechanical link and that the work in this direction should be continued.

2.4. Course control channel

In connection with the fly–by–wire aircraft it turned out to be necessary to consider the possibility and effectiveness of the side stick directional control. There are no data on the side stick course control in literature, that is why the authors conducted a number of experiments aimed at assessing aircraft handling qualities in the directional channel, using the side stick. In the experiments the side stick had, beside the roll and pitch channels, also the third DOF for the directional control.

Let us consider the results of such a side stick investigations and the conclusions drawn there from different combinations of the controlling components.

For the one channel side stick course control the data in Fig.2.10 show the control precision considerably higher (by 10–40 %) than the conventional control levers. Evidently, this is attributed to a considerably less pilot's lag in the side stick control case, as compared with the conventional lever control, i.e. the side stick manifests clearly dynamic superiority with respect to the levers.

However the isolated yaw control problem is rare in practice and is more interesting in methodological sense. Therefore, the side stick aided aircraft control effectiveness was assessed for the problems of full lateral motion control, e.g. when refueling.

In experiments on two–channel roll control the pilot controlled the aircraft first using the side stick, and then – the levers directionally and the side stick in roll. The results of the experiment are given in Fig.2.11.

As it is seen, the side stick advantage for the directional control remains in this problem as well. We just note here a certain (by 5 – 20%) roll stabilization precision degradation for the solely side stick control. This may be attributed to the complication of the pilot's roll control motion when the latter are combined with the directional degree control (for the lever type side stick being considered). This can play a negative role when performing other piloting mission, for example landing and approach, where high precision of the roll setting is required.

Three channel control of the full aircraft motion using the three–degree OF stick (pitch, roll and yaw) was investigated for the approach problem. the experimental results are also given in fig.2.12. The show that the three channel control using the three DOF stick is possible, but in yaw and roll trimming is inferior to using levers in direction and the side stick in roll and pitch.

According to the pilot's remarks, the three–channel side stick aided control turns out to be informationally overloaded and requires additional hand switch to actions in the third channel. As a result, the pilot is forced to work not on the under consciousness stereotype level, but consciously, which makes control action generation more difficult, and may manifest itself in difficult flight conditions in emergency situations.

Piloting comfort, accuracy and reliability determine the expediency of the side control stick application in the yaw. At one–channel yaw control there have never been any inconvenience.

Pilots have considerable difficulties at combined roll and yaw control,

in the conditions of asymmetric arm operation. Simultaneous left roll motion and yaw motion to the right is especially difficult. These two motion combination is rather complicated and pilots have to think it over, which is needless in the case of the yaw control by means of pedals.

Thus, the expediency to neglect pedals in the yaw control in favour of the side stick third degree for non–maneuver airplanes seems doubtful, as it cause a fall of piloting

precision (particularly in roll), complicates the control process, and entails inconvenience in pilots' operation.

At the same time, the side stick instead of the pedals in one—channel control for some special tracking tasks may well happen effective and expedient.

2.5 Force trimming

Control system generation is known to be essentially dependent on the selection of the trimming forces type. According to the pilots opinion, for the effective utilization of the side control stick, it is expedient to provide the possibility of the manual effort trimming in the horizontal flight. As it is known, the A—320 airplane employs the automatic effort trimming, but the manual trimming necessity may well arise in case of the zero transducer data output.

Realization of the trimming forces of the central stick type, i.e with the variation of the neutral (with the balance effort) stick position requires presence of the corresponding trimming mechanism, which complicates in essential way the side control stick design, enlarges its dimensions, but does not provide the pilot with the essential information due to the small side stick displacements. That is why the other trimming type, the so—called electric, is preferable, when the trimming signal is formed, which, after summation with the signal coming from the side control stick replaces its part at the entrance of the manual control (Fig.2.13). As a result, the pilot decreases for the corresponding value, the effort applied to the side control stick, that is, trims it.

The drawback of the electric trimming is the fact that it causes unavoidable distortions of motion parameters, because estimating and keeping the required trimming rate by the pilot is possible by only varying (distorting) the flight parameters being kept. And the higher the rate, the higher is the level of distortions being introduced. That is why they try to diminish the trimming rate, in order to diminish the interference level. On the other hand, it should not be arbitrarily small, for the trimming process not to be too long in time.

For simplification of the side control stick trimming pilot effort one can use different schemes. For instance, one can organize relatively simply the semi—automatic trimming regime, which is accomplished by simply pressing a two—position button (Fig.2.14). Selection of the trimming direction is accomplished here automatically, according to the signal sign, coming from the side control stick. Here, the trimming rate may be both constant and variable, proportional to the side control stick output signal. Such a trimming type was worked out if flight laboratory flights and deserved high pilot estimates, but not all the questions are clear enough. So for example, for the separated trimming in pitch and roll, two buttons are needed, which is very inconvenient. It is not deprived of the drawbacks, noted earlier.

In connection with this a problem arises, of developing a way of the automatic trimming with the minimum distortion level in the aircraft motion parameters. At present, at TsAGI the trimming technique is developed, which permits to trim forces practically instantaneously, without any distortions of the motion parameters being kept. Schemes, realizing this technique, and the motion parameter variation recorded when trimming are given in Fig.2.15.

3. THE THEORETICAL APPROACH TO CHOOSING THE OPTIMUM CONTROL SENSITIVITY AND LOADING CHARACTERISTICS OF A SIDE STICK

It is not so easy in practice to choose the optimum values of control sensitivity and lever loading characteristics since they depend complicatedly not only upon each other but also upon class of aircraft and type of a control lever, the piloting task and aircraft dynamic characteristics. Along with that the characteristics of lever loading and control sensitivity have the definite effect on the aircraft controllability and flight safety. Therefore the development of methods to optimize the characteristics of lever loading and control sensitivity is the problem of great practice importance. A lack of such methods restrains essentially a development of manual control optimization theory as a whole.

At present there is no sufficiently general theory or technique of calculation permitting to make choice of optimum characteristics of control sensitivity and loading not only for side stick but also for another control levers. In the Standards there are only the limits of some of them, which are admissible by safety condition. As to optimum values of lever loading and control sensitivity characteristics, they are chosen experimentally with due regard for the practice of developing the aircraft close to each other in class and purpose [1−5]. Earlier when the dynamic structure and the aircraft control levers (wheel of transport aircraft, central stick of fighters, pedals) remained practically unchanged these characteristics could have been roughly chosen on the basis of practice of developing the aircraft of the previous generation. Their required refinements could have been made in flight testing. This approach becomes inadequate these recent years due to the incorporation of automatics in the loop of a manual control, the appearance of nontraditional dynamic structures and new control levers (including a side stick), the extension of the possible region of the aircraft stability and controllability characteristics [2,3]. To choose the characteristics of the aircraft yet at the first stage of its design and also to narrow the scope of characteristics to be studied during the follow−on experiments it became quite necessary to develop theoretical methods of optimizing the characteristics of lever loading and sensitivity of control.

The admissible maximum forces and displacements of traditional control levers which are necessary for the pilot to perform manoeuvers with large accelerations or to counteract failures and strong gusts are depicted in literature and specifications [4,5]. For the new control levers these admissible values may sufficiently easy be estimated by the physiological possibilities of a pilot [6]. Morë complicated and less studied is the problem of optimum characteristics of lever loading and control sensitivity in the tasks of the aircraft stabilization when the pilot is in the continuous tracking mode and he has to perform small but exact actions with the control levers. Solution of this problem is usually crucial at choosing the characteristics of lever loading and control sensitivity and causes the great difficulties in practice.

To state the theoretical approach to choosing the control sensitivity and side stick loading characteristics being optimum on conditions of stabilization task and with regard for their dependence upon dynamic performances, is the chief object of this part of the report. The stated theoretical approach is the summarizing, subsequent development and specification of results of Ref.[7 − 9] for side stick applications.

3.1. Properties of pilot as a link of control system and basic theses of approach.

3.1.1. Preliminary remarks.

Generally speaking, taking into account the dynamic performances of linkage, lever loading can be described by complicated differential equations with great number of parameters. The form of the equations and the number of parameters are dependent on type of control system (with or without boosters, fly—by—wire system or mechanical linkage) and its specific characteristics (Fig.3.1). While definition the optimal lever loading at stabilization task, when lever displacements X and applied forces F around neutral or trim lever position are small, it may be described by loading gradient F^x, breakout force F_0, coulomb friction force F_{fr}, mass m and coefficient of loading damping $F^{\dot{x}}$. The loading of this type is under consideration herein. It is described by the following expression:

$$m\ddot{X} = F^x X + F_0 \mathrm{sign}X + F_{fr}\mathrm{sign}\dot{X} + F^{\dot{X}}\dot{X} \qquad (3.1)$$

(An expression for the force friction at $\dot{X} = 0$ is not used later on and, therefore, is not presented here.) The static characteristic of the lever loading is given in Fig.3.2.

The sensitivity of control characterizes the intensity of the airplane's responses to the forces applied by the pilot to the control levers or to their displacements. Nowadays various parameters are used as control sensitivity characteristics for various cases. The sensitivity of control of the airplanes of a traditional configuration is usually characterized by the rate of forces or displacements per unity of an increment of values of a normal g—load n_z and an angular velocity of roll p respectively in the longitudinal and lateral control channels of the airplane

$$F_{n_z} = \lim_{t\to\infty} \Delta F / \Delta n_z; \quad F_p = \lim_{t\to\infty} \Delta F / \Delta p \quad \text{etc.}$$

Along with these characteristics there are also used in Russia as control sensitivity characteristics the displacements of a control lever X_{n_z}, X_p which are connected with F_{n_z} and F_p by the following expressions:

$$F_{n_z} = F^x \cdot X_{n_z}; \quad F_p = F^x \cdot X_p$$

These characteristics are easy defined during a flight. Besides, at small values of loading gradient a pilot is guided mostly by displacements of control lever. That is why we will use later on both F_{n_z}, F_p and X_{n_z}, X_p.

For the aircraft with non—traditional dynamic characteristics, for example for VTOL aircraft, and also in studying the model objects of control, other characteristics of control sensitivity are used: a ratio of displacements or forces applied to control lever per g—load or angular acceleration arising at the first moment ($X_q = \lim_{t\to 0} \Delta X / \Delta q$ e.t.c.), the transfer coefficient K_{tr} between lever displacements and control surface deflection, the gain coefficient in aircraft transfer function and others.

For expounding the problems common for different aircraft, we will use later on the symbols F^r or X^r to indicate any control sensitivity characteristics.

3.1.2. The optimization principles of forces and displacements.

The following properties of the pilot as the link of the system "airplane—pilot" make a basis of a theoretical approach that will be stated further.

1. Of great importance for the pilot when piloting are both the applied forces F and the displacements X of the control lever.

   In other words, there are optimum (desirable) from a pilot's point of view values of the applied F_* forces and displacements X_* of the airplane's control levers.

   This follows, for example, from the pilot ratings regions presented in Fig.3.3 in terms of aircraft control sensitivity to side stick forces and displacements. They are plotted according to the experimental data presented in Fig.3.4 – 3.5, which were obtained in the work with one participating pilot while modelling the landing approach regime.

   In the Fig.3.3 in the plane of longitudinal F_{n_z}, X_{n_z} and lateral F_p, X_p control sensitivity characteristics there are presented the pilot ratings of airplane with various gradients of side stick loading $F^x = F_{n_z}/X_{n_z}$, $F^x = F_p/X_p$. It is seen that the pilot can handle an unmoving control lever ($F^x \to \infty$) as well as the control lever the deflection of which requires no forces ($F^x = F_0 = F_{fr} = F^{\dot{x}} = 0$). But the best controllability is reached only at certain relation of forces and displacements of the control lever. Under such forces and displacements the most favourable conditions are created for pilot operation.

   Under the given limitations for certain characteristics of lever loading and sensitivity of control the pilot selects other (which have to be optimum) characteristics such that applied forces and displacements realized in piloting were equal or close to their desirable values, as it is seen, for example, in Fig.3.3. In order to provide the desirable level of the applied forces, if there are no other possibilities, the pilot estimates positively even lever loading characteristics which has no direct relation with the transfer of control effects, for example, a certain level of coulomb friction.

2. While estimating the optimum lever loading and control sensitivity characteristics a pilot causes usually the aircraft motion to be harmonic one with characteristic frequency ω_* and amplitude A_* which do not depend upon aircraft dynamic properties.

   It is seen, for example, in Fig.3.6 and 3.7, where there are presented the experimental data obtained in piloting task with different dynamic performances when an atmospheric turbulence was absent and pilot was deflecting the control lever to estimate the control sensitivity. In Fig.3.6 there are given the record of piloting parameters, and in Fig.3.7 – the spectral density of the process. It should be mentioned that under performing the task of stabilization in presence of atmospheric turbulence, a pilot deflects a control lever within narrow frequency band, i.e. makes control lever motion to be like sinusoidal one.

3. The worsening of controllability with an increase of forces and displacements above this optimum level is linked with limited possibilities of the human to create strong forces and displacements of levers, and with their decrease it is linked with the problems of dosage of the control forces and displacements, high influence of the pilot's unintentional actions on piloting, airplane's construction vibrations and other factors.

   At large deviations of forces and displacements from their optimum values the aircraft controllability is worsening by Weber–Fechner psychophysiological law. Using the following expression one can estimate the pilot ratings worsening:

$$\Delta PR = a\left|\lg\frac{F}{F_*}\right| + b\left|\lg\frac{X}{X_*}\right|$$

At small deviations of lever forces and displacements from their optimum values the pilot ratings alteration is not so intensive and has other disposition. In this case the pilot ratings worsening can be described by an expression:

$$\Delta PR = f \cdot lg^2 \frac{F}{F_*} + g \cdot lg^2 \frac{X}{X_*},$$

where ΔPR — the pilot ratings alteration in accordance with Cooper—Harper pilot ratings scale; a , b , f , g — the constants.

It is seen, for example, from the experimental data have been considered (Fig.3.4, 3.5) for the side stick and from Fig.3.8 as well, where the dependencies are presented of pilot ratings upon control sensitivity characteristics not only for a side stick but also for other control levers at different conditions (for different aircraft classes, control channels and piloting tasks, at different dinámic performances, different lever loading characteristics , e.t.c.). The similar dependency as applied to the control sensitivity is given in Ref.[10].

Generalizing these well—known properties of the pilot one may formulate the following three principles of lever loading and control sensitivity characteristics optimization:

1. The principle of optimum forces and displacements.

   Let us consider F, X to be available forces and displacements of control lever, J — a function which determines the extent of their deviation from desirable values of forces F_* and displacements X_* . In this case as optimum in controllability one select such values of the lever loading characteristics under which the fulfilment of the considered piloting mission is reached at a minimum deviation of forces and displacements from some constant desirable values, i.e. at which the minimum of fuction J is reached (Fig.3.9):

   $$J_* = \min_{F^x, X^r, \dots} J \qquad (3.2)$$

2. The principle of characteristic piloting task.

   While choosing the lever loading and control sensitivity characteristics the aircraft sinusoidal motion may be taken as the considered piloting task with some characteristic frenquency ω_* and amplitudeA_*, which do not depend upon aircraft dynamic performances, i.e.

   $$X = A_X \cdot \sin \omega_* t; \qquad (3.3)$$
   $$c = A_* \cdot \sin(\omega_* t + \varphi)'$$

   where A_X — the amplitude of lever displacement, c — the parameter under controlling. A_* and ω_* — the constants which do not depend upon aircraft dynamic performances and control lever type. The constants' values may change depending on aircraft class and control channel.

3. The principle of controllability worsening.

   At deviation of lever loading and control sensitivity characteristics from their optimum values, the controllability worsening can be approximately estimated according to the formulae:

   at large deviations of $X/_{X_*}$, $F/_{F_*}$ from 1:

   $$\Delta PR = a\left|\lg F/_{F_*}\right| + b\left|\lg X/_{X_*}\right|, \qquad (3.4a)$$

   at little deviations of these characteristics from 1:

$$\Delta PR = f \cdot \lg^2 \frac{F}{F_*} + g \cdot \lg^2 \frac{X}{X_*}. \quad (3.4b)$$

These principles are virtually the essence of the theoretical approach that are stated in the report.

It should be mentioned that the second principle is not obligatory but auxiliary one only. Generally speaking, other piloting tasks may be chosen as a characteristic piloting task, for example, the aircraft stabilization task, as it has been done in Ref.[7,8,11]. The use of different piloting tasks leads to similar results, that will be shown in section 3.2. However, the use of sinusoidal motion as a characteristic one simplifies essentially the mathematical side of the theoretical approach expounded herein.

It is necessary to note also the following. Experience and experimental data show that a change of loading and control sensitivity characteristics over a wide range does not exert influence upon piloting accuracy: many times change of the characteristics, as it is shown in Fig.3.10, can cause a change of piloting accuracy by a few percent only. The entire aviation experience indicates it: in spite of essential differences of lever characteristics, control sensitivity and dynamic characteristics of different aircraft, the piloting, for example, in approach and landing, is performed with the same quality. Only pilot ratings are essentially dependent upon these charateristics. It is explained by that a pilot, at any price and to the detriment of his own physical expenses, seeks to provide the necessary piloting accuracy.

In connection with this, while optimizing the loading and control sensitivity characteristics one can consider that the piloting accuracy parameters do not depend on lever loading, control sensitivity and dynamic performances, and the function J, in its turn, depends on a difference between experienced and desirable forces and displacements only, i.e. J does not depend on piloting accuracy. For this reason the results obtained according to the stated theoretical approach depend little on the piloting task chosen to be as the characteristic one.

The specification will be given later on of the principles that have been formulated (a precise definition and possible mathematical expression for the used conceptions) and subsequent validation of their reliability on the basis of comparison of calculated and experimental data on controllability of unmanoeuvrable aircraft equipped with a side stick.

3.2. Criteria of controllability

The loading and control sensitivity characteristics' values, optimum by pilot ratings, depend essentially and complicatedly upon each other and aircraft dynamic performances. Because of great number of parameters they can not be defined in experiments and presented in tables for all aircraft characteristics. The criteria under consideration allow to define easy by calculation with a help of few empirical constants the optimum lever loading and control sensitivity characteristics taking into account their interdependency and a dependence of control sensitivity upon dynamic performances. They allow as well to estimate the worsening of aircraft controllability at deviation of control sensitivity characteristics from their optimum values.

The criteria under consideration are one of the possible specification of the principles stated above.

3.2.1. The criterion for choosing optimum lever loading characteristics.

We call it "Z–criterion" by the first letter of the word "loading" in the Latin transcription of Russian word "zagruzka".

Before expounding its essence we should mention the following. As a result of contraction of the muscle tissue or displacement of some body parts, say shoulder, and also as a result of the fact that any forces of the man are due to the contraction of the muscles with the signals about the magnitude and speed of these displacements passing to the central nervous system, the pilot when handling even stationary lever (when the control surface is deflected by a signal of forces) has some sensations similar to those that occur at the movement of the lever. Let us consider that these fictive displacements are proportional to the forces applied to the lever

$$X_f = c \cdot F \tag{3.5}$$

and that the experienced displacements represent a sum of real X and fictive X_f displacements of the lever, i.e.

$$X_e = X + X_f \tag{3.6}$$

As the degree of proximity of experienced (F, X_e) and desirable (F_*, X_*) levels of forces and displacements the different function J may be used. But in any case for their using in the considered criterion it is necessary for them to reach their minimum at $X_e = X_*, F = F_*$ and to increase monotonously at deviation F, X_e from F_*, X_* to greater or lesser values. In this work the degree of deviation of the levels of forces and displacements from their optimum desirable levels we will define by a function of the type:

$$J = (F - F_*)^2 + K(X_e - X_*)^2, \tag{3.7}$$

where K – the constant weight coefficient.

At small deviations of F, X_e from F_*, X_* this function in a first degree of approximation is equal to the function (3.4). One should see it taking into account that

$$\lg^2 \frac{F}{F_*} = \left(\lg\left[1 - \left(1 - \frac{F}{F_*}\right)\right]\right)^2 \sim \left(1 - \frac{F}{F_*}\right)^2 = \frac{(F - F_*)^2}{F_*^2}$$

$$\lg^2 \frac{X_e}{X_*} = \left(\lg\left[1 - \left(1 - \frac{X_e}{X_*}\right)\right]\right)^2 \sim \left(1 - \frac{X_e}{X_*}\right)^2 = \frac{(X_e - X_*)^2}{X_*^2}$$

Therefore, the function J (3.7), essentially, characterizes the degree of controllability worsening at small deviations of forces and displacements from their desirable levels.

The function (3.4) may be used as the function J. But this would complicate the mathematical side of Z–criterion and would not lead to calculation accuracy improvement.

In order with the use of the Z–criteria to estimate by calculating the optimum loading control sensitivity characteristics it is necessary to define the dependencies of forces F and displacements X_e upon these characteristics:

$$F = F\left(F^x, X^r, \ldots\right)$$

$$X_e = X_e\left(F^x, X^r, \ldots\right)$$

To determine the dependencies let us consider the sinusoidal motion to be the characteristic piloting task (3.3) in accordance with the second principle of optimization. To characterize forces and displacements of lever we will use their maximum values realized by a pilot while performing the sinusoidal motion. Taking into consideration the loading law (3.1) we have:

$$X = A_x$$

$$F = F_0 + F_{fr} + A_x \sqrt{\left(F^x - m\omega_*^2\right)^2 + \left(F^{\dot{x}}\omega_*\right)^2} \qquad (3.8)$$

The amplitude of lever displacement Ax may be conveyed through the amplitude of controlled parameter A_* according to the expression:

$$A_x = A_* \left| W_{c/x} \right|^{-1}, \qquad (3.9)$$

where $W_{c/x}$ – the aircraft transfer function, A_* – the constant (according to the principle 2).

Since the parameter X^r presents at the transfer function $W_{c/x}$ as a factor $\left(X^r\right)^{-1}$, this transfer function may be written as

$$W_{c/x} = \frac{\overline{W}_{c/x}}{X^r}, \qquad (3.10)$$

where $\overline{W}_{c/x}$ – the aircraft transfer function divided by parameter $\left(X^r\right)^{-1}$ and independent upon lever loading and control sensitivity characteristics.

Thus, taking into account (3.8) – (3.10), the function (3.6) assumes the following type:

$$J = \left(F_0 + F_{fr} + \frac{A_*}{\left|\overline{W}\right|} X^r \sqrt{\left(F^x - m\omega_*^2\right)^2 + \left(F^{\dot{x}}\omega_*\right)^2} - F_* \right)^2 +$$
$$+K \cdot \left(\frac{A_*}{\left|\overline{W}\right|} \cdot X^r + c\left(F_0 + F_{fr} + \frac{A_*}{\left|\overline{W}\right|} \cdot X^r \sqrt{\left(F^x - m\omega_*^2\right)^2 + \left(F^{\dot{x}}\omega_*\right)^2} \right) - X_* \right)^2. \qquad (3.11)$$

So, in accordance with the above mentioned the essense of Z–criterion may be formulated in the following way. As optimum value of one or another characteristics of lever loading that one is chosen which corresponds to the minimum of the function (3.11).

It is reasonable to mention the following. If a task of stabilization is chosen to be as the characteristic one, as it was chosen in Ref.[11], the function (3.11) has the following type (in case m=0):

$$J = \left[F_0 + F_{fr} + \left(aF^x + bF^{\dot{x}}\right)X^r - F_*\right]^2 +$$

$$+ K\left[aX^r + c\left(F_0 + F_{fr} + \left(aF^x + bF^{\dot{x}}\right)X^r\right) - X_*\right]^2$$

A comparison of this expession with the function (3.11) shows that they differ each other when considering the loading damping. It is evidence of that a choice of the characteristic piloting task does not reflect on the final optimization result in the stated theoretical approach.

The proposed criterion not only qualitatively but quantitatively reflects known experimental data of optimum control sensitivity and loading characteristics of different control levers. Some examples which are indicative of a high efficiency of Z–criterion will be presented in the following parts of the report.

In practice when optimizing the lever loading and control sensitivity characteristics the values of some of them are given (for example, the force of coulomb friction in a linkage), and the others are the free parameters which may be defined. The free para– meters may have one or another limitation which is determined by different reasons. Therefore the definition of optimum loading and control sensitivity characterisitcs is, in essence, the minimizing of the nonlinear function (3.11) on one or few free parameters $(F^x, F^r, \ldots)$ which have some limitations. A mathematical procedure of searching the optimum solution of the task (i.e. searching the minimum of a function with many variable quantities) is well known and, therefore, is not considered herein.

3.2.2. The criterion of optimum control sensitivity characteristics.

The idea of this criterion, which we call an A–criteria from the word combination "amplitude–frequency", is in the following. The optimum values of the characteristics of the control sensitivity for different dynamic characteristics of the airplane ($\varsigma, \omega,$) are defined from the condition:

$$\left|W\left(j\omega_*, X^r_{opt}, \varsigma, \omega \ldots\right)\right|^{-1} = A = \text{const} \tag{3.12}$$

$$A = \frac{1}{A_*}\frac{\sqrt{\left(F^x - m\omega_*^2\right)^2 + \left(F^{\dot{x}}\omega_*\right)^2}\left(F_* - F_0 - F_{fr}\right) + K\left(1 + c\sqrt{\left(F^x - m\omega_*^2\right)^2 + \left(F^{\dot{x}}\omega_*\right)^2}\right)\left(X_* - cF_0 - cF_{fr}\right)}{\left(F^x - m\omega_*^2\right)^2 + \left(F^{\dot{x}}\omega_*\right)^2 + K\left(1 + c\sqrt{\left(F^x - m\omega_*^2\right)^2 + \left(F^{\dot{x}}\omega_*\right)^2}\right)^2}$$

where $\left|W\left(j\omega_*, X^r_{opt}, \varsigma, \omega, \ldots\right)\right|$ – a value of the amplitude frequency characteristic of the airplane's transfer function of the control lever displacement relative to some phase coordinate of the airplane or its derivative at a characteristic frequency ω_*. As a coordinate of such type the one is adopted that plays the major role in the piloting mission under study.

The physical idea of the A–criteria is that at the optimum values of the control sensitivity characteristics the relationship between the amplitude of the control lever movements A_x following the law of harmonics and the amplitude A_* of the signal c(t) on a characteristic frequency (i.e., $A_x / A_* = |W|^{-1}$) remains equal for various dynamic characteristics of the airplane. It is indicated by the amplitude – frequency characteristics (AFC) of lateral control channel of the airplane of Il96–300 type depicted in Fig.3.11. They are defined for the optimum control sensitivity values, different dynamic performances and different flight regimes. It is seen that, in spite of flight regimes and dynamic performances variety, AFC of the transfer function

appearing in the A−criterion (3.12) cross in narrow area: approximately in one and the same point − 8.1 mm/deg at frequency $\omega_* = 1.25\ s^{-1}$. A−criterion, i.e. the expression (3.12), is derived from the condition of the function J being minimum along the parameter X^r. Thus, A−criterion is a particular case of Z−criterion. The criteria have the different names since they are intended to solve the different tasks: Z−criterion − for choosing the optimum loading characteristics and A−criterion − for choosing the optimum control sensitivity characteristics.

Numerical values of the parameters that are in the A−criterion and the examples indicating the efficiency of the criterion will be given in the following parts of the report.

Consider now the problem concerning the controllability worsening at deviation of control sensitivity characteristics from their optimum values.

As it follows from (3.4) and experimental data (Fig.3.8), the worsening of the controllability may be estimated in accordance with the following:

$$\Delta PR = \begin{cases} -6\lg X^r/X^r_{opt} - 1.5 & \text{at } X^r/X^r_{opt} \le 0.5 \\ 6\lg^2 X^r/X^r_{opt} & \text{at } 0.5 \le X^r/X^r_{opt} \le 1 \\ 9\lg^2 X^r/X^r_{opt} & \text{at } 1 \le X^r/X^r_{opt} \le 2 \\ 9\lg X^r/X^r_{opt} - 2 & \text{at } X^r/X^r_{opt} \ge 2 \end{cases}$$

As it is seen from this formula and experimental data (Fig.3.8), there exists a sufficiently wide range of control sensitivity characteristics within which the pilot ratings are close to optimum and depend weakly upon values of these characteristics. As experiments show, the pilots do not notice any difference in aircraft controllability at variation of the control sensitivity characteristics by about 10−15%. With a deviation of sensitivity characteristics from their optimum range the pilot ratings are getting sharply worse. With an increase of the control sensitivity (for example, decrease of F^r) the PIO tendency arises, and with a decrease of the control sensitivity pilots estimate the airplane as being sluggish and tiresome in control and complain of drawback in the efficiency of control.

One should mind that this design dependency reflects but a general tendency of variation of the pilot ratings with a variation of the control sensitivity characteristics. Depending upon particular conditions the pilot ratings may somewhat differ from this dependency.

These deviation are due to individual peculiarities of the pilot, characteristics of lever loading and some other factors.

The influence of the control sensitivity characteristics on the aircraft controllability when performing the mission of stabilization may be explained by analyzing the experimental frequency characteristics of the "airplane−pilot" system. The analysis of the characteristics has shown that within a certain range of variation of the aircraft gain coefficient (i.e. control sensitivity) the pilot easily adapts himself for a variation of control sensitivity and adjusts his gain coefficient so that the total gain coefficient kK and cut−off frequency remain practically constant (Fig.3.12). In this connection within a definite range of variation of the control sensitivity characteristics the pilot ratings vary insignificantly. At a decrease of the control sensitivity starting approximately from the values of three times lower than the optimum, the pilot can no longer increase his gain coefficient due to physiological reasons and limited displacements of the control

levers. Therefore the total gain coefficient of the airplane—pilot system decreases resulting in a decrease of cut—off frequency, speed and accuracy of piloting. As a result the pilot estimates the airplane as being sluggish with an insufficiently efficient control and lowers the pilot ratings. With an increase of the control sensitivity by about 3 times and more there is a considerable decrease of the level of the displacements and forces exerted by the pilot. They become comparable with thresholds values, the dynamic of actions acquires a non—linear character, the remnant component of the pilot's actions increases and the pilot— aircraft system reaches the limits of stability. And by this is explained the worsening of the pilot ratings at an increased sensitivity of control.

3.2.3. The remarks concerning a choice of the parameters belonging to the criteria.

As it is seen from expressions (3.11) and (3.13), to have a possibility of definition of the numerical values of optimum loading characteristics, it is necessary to know the values of the parameters W, A_*, ω_*, K, c, F_*, X_*, belonging to this function.

W is determined by what a coordinate is under control at the moment or what a coordinate plays the major role in the given piloting task.

A_* and ω_* do not depend on the aircraft dynamic characteristics, lever loading and control sensitivity characteristics. As it has been mentioned already, the values of A_* and ω_* depend on the aircraft class and control channel. The values ω_* and A_* can be chosen from the condition of the best correlation of experimental and data calculated using A—criterion. Generally speaking, for the choosing it is enough to have the experimental data for two different dynamic configurations only ($\varsigma, \omega,$). However, because of inevitable mistakes of experimental definition of optimum control sensitivity characteristics and possible approximate character of A—criterion it is reasonably to choose the values ω_* and A_* according to more number of dynamic configurations. To attach an equal importance to a dispersion of experimental data obtained in different conditions, it is reasonably to choose the values ω_* and A_* from the condition of minimum dispersion of $\left|W(j\omega_*)\right|^{-1}$ at the characteristic frequency, in contrast to the condition of minimum deviations of experimental optimum sensitivity characteristics from calculated values, i.e.

$$\min_{\omega_*, A_*} \frac{1}{N} \sum_{i=1}^{N} \left[\left| W\left(j\omega_*, X^r_{i_{opt}}, \varsigma, \omega, \ldots\right) \right|^{-1} - A_* \right]^2$$

The parameters K, c, F_*, X_* do not depend on the characteristics of lever loading and control sensitivity. They are defined only by the type of the lever and control channel or, to be more exact, by physiologocal possibilities of the pilot to creat forces and displacements. Their values may be defined from the condition of the best coincidence of experimental data and data calculated according to Z—criterion. At present there are no in publications sufficiently complete data on optimum values of different loading characteristics, which are necessary for an accurate definition of all these parameters as applied to different aircraft control levers. Nevertheless, on the basis of available materials the approximate estimation can be made of the parameters K, c, F_*, X_* belonging to (3.12).

Let us represent a coefficient K to be $K = æ\left[F_*/X_*\right]^2$. A comparison of calculated and available experimental data for some control levers and channels has shown, that for all lever types and control channels the values of the parameter æ is approximately equal and can be accepted to be æ = 1. The desirable levels of applied forces and

displacements of lever, i.e. F_* and X_* depend on lever type and control channel. If the values of F_{*_i} and X_{*_i} are known for one lever, their values for other control levers can be approximately determined proceeding from the data on maximum values of the man-attained forces and displacements while handling the different control levers F_{max_i}, X_{max_i} according to the following: F_{*_i}/F_{max_i} = const, X_{*_i}/X_{max_i} = const. The available materials give us a reason to consider the ratio F_{*_i}/F_{max_i}, X_{*_i}/X_{max_i} to be approximately equal for different control levers.

The values F_{max_i} and X_{max_i} are set in literature, for example Ref.[6]. They are dependent not only on whether one or two arms or legs participate in controlling but also the location of the control lever relative to the pilot. For example the control with the use of the wheel is performed by both arms while with the use of the central stick by one arm. With two arms a man can exert maximum forces by about 1.5–2 times larger than with one arm, while the possible margin for the movement of arms is roughly the same for both cases. These considerations as well as the comparison of the calculated and available data allow to assume the values F_* and X_* for the longitudinal channel of a wheel, central and side sticks of transport aircraft as being equal to those set in Table 3.1.

Table 3.1

Characteristics	Wheel	Central stick	Side stick
F_*, kg	6	3–4	1.5
X_*, mm	25	25	20

3.3. Recommendations for choosing the side stick loading characteristics

3.3.1. Loading gradient.

Among different characteristics of loading of the control levers, loading gradient is most important. This is due to the fact that along with a possibility of providing the optimum level of controlling forces and displacements, along with centering features the loading gradient permits also better than other loading characteristics to make a dosage of the controlling actions since the aircraft response in this case is in proportion to the magnitude of the lever displacement and to the magnitude of the applied forces.

In order the control lever to have the feature to return to central position and to fix being there, the gradient value must be positive $F^x > 0$. Taking this into account; from Z–criterion, that means from the condition of the minimum of the function (3.11)

$$F^x_{opt} = \frac{F_* - (1 + K \cdot c)(F_0 + F_{fr}) + K \cdot c\left(X_* - A_*\overline{X}^r\right)}{A_*\overline{X}^r (1 + K \cdot c)}, \qquad (3.13)$$

$$\text{where}\,\overline{X}^r = X^r \cdot \left|\overline{W}(j\omega_*)\right|^{-1}, \left(F^{\dot{x}} = m = 0\right).$$

This expression is valid when the numerator is great or equal to zero. Otherwise the optimum F^x is equal to zero.

It is seen from here that the optimum loading gradient is a function of other characteristics of loading and control sensitivity. With an increase of the values of the breakout force F_o , coulomb friction F_{fr} , loading damping $F^{\dot{x}}$, sensitivity of control X^r, the optimum values of the loading gradient decrease. The dependency (3.13) well correlates with experimental data, for example with data shown in Fig.3.3.

At optimum value of control sensitivity X^r from Z–criterion, i.e. from the condition of minimum of the function (3.11) along parameters F^x and $\overline{X}^r$

$$\frac{\partial J}{\partial F^x} = \frac{\partial J}{\partial \overline{X}^r} = 0$$

for the case $F^{\dot{x}} = F_0 = F_{fr} = m = 0$ and taking into account the small value of the constant c , we approximately have

$$F^x_{opt}\left(X^r = X^r_{opt}, F^{\dot{x}} = F_0 = F_{fr} = 0\right) = \frac{F_*}{X_*}$$

As the desirable levels of forces and displacements F_* and X_* depend upon lever type, from the expression (3.13) one should learn that the optimum loading gradient values are diverse for different control levers. The ranges of optimum loading gradient values of the main control levers at F_0, F_{fr}, $F^{\dot{x}}$ close to zero and optimum control sensitivity are given in the Table 3.2.

Table 3.2

Control channel	Wheel	Central stick	Side stick	Pedals
Longitudinal, kg/mm	0,15...0,35	0,08...0,25	0,05...0,20	0,2...0,5
Lateral, kg/mm	0,05...0,1	0,05...0,2	0,04...0,15	

The data on a side stick given in the Table correlate with the results of experiments on flight simulator (Fig.3.3, 3.12). In Fig.3.12 there are presented the values of side stick

optimum loading gradient in longitudinal and lateral channels, obtained in flight tests on in−flight simulator Tu−154M with a participation of authors of the report. It should be mentioned that to assess a trustworthiness of obtained results, both on ground and in−flight simulators one and the same pilot participated and one and the same side stick was used. In Fig.3.13 there are located the data on the side stick of aircraft A−320. A coincidence the presented data confirms a trustworthiness of obtained regions of acceptable side stick loading characteristics and Z−criterion stated herein.

At a deviation of loading gradient from their optimum values the controllability is getting worse as it is shown in Fig.3.14. Controllability becomes especially worse at a decrease of the loading gradient, i.e., the control at $F^x \to \infty$ is estimated by the pilot much better than at $F^x = 0$. This correlates with the practical experience. There are airplanes like, for example, the F−16 with an stationary stick, i.e. $F^x \to \infty$. For the case of jamming the control linkage redundancy control is foreseen when a control surface is deflected by the signals of the forces which are in fact applied to a stationary control lever. However there is no information of the cases when the gradient of lever loading had a zero value.

3.3.2. Breakout force.

The breakout force is usually introduced with an aim of centering and fixing the control lever. From the expression (3.1) it follows that when the pilot does not apply any forces to the lever ($F = 0$), it will turn to central position and fix in position $X = 0$ if the value of breakout force is greater that coulomb friction ($F_0 > F_{fr}$). With this purpose the magnitude of breakout force is usually taken greater than the magnitude of friction in the linkage. But even in the absence of friction certain magnitudes of breakout force make the controllability to be better. It is seen, for example, from the results presented in Fig.3.15 and 3.16.

As analysis shows of available and obtained experimental data, in absense of coulomb friction the optimum values of breakout force in longitudinal channel are approximately equal to 0.5 kg for a side stick, 0.7kg for a central stick and 1 kg for a wheel.

A difference of optimum values of breakout force for a wheel, central and side sticks are connected, first of all, with the human possibilities to create forces with different control levers. In lateral channel the optimum breakout forces of central and side stick are approximately the same that they are in longitudinal channel, in spite of the fact that the force possibilities of a human differ in about 1.5−2 times. It is connected with that when piloting the pilot needs to apply the great forces in longitudinal channel. As a result in lateral channel "interferences" may be large which are involuntary created by a pilot at handling in longitudinal channel. It is confirmed by flight tests and data of experience. For airplane A−320 the side stick breakout forces are equal: in longitudinal channel $F_o = 0.4$ kg, in lateral channel $F_o = 0.6$ kg. According to the results of flight researches in in−flight simulator Tu−154M the optimum values of breakout force are equal to $F_o = 0.4$ kg in longitudinal channel and $F_o = 0.3$ kg in lateral channel.

The introduction of the breakout force is useful, first of all, in those cases when for some reasons too small force gradients or too large control sensitivity are realized, that is when the level of the forces applied by the pilot in piloting turns out to be considerably less than the desirable value. This is evident from the Z−criteria. Indeed, from the minimum of the function (3.11) along F_0, taking into account that according to the condition of centering and fixing of control lever the condition $F_0 > 0$ must be provided, one can get the following expression (at $F^{\dot{x}} = m = 0$):

$$F_{0_{opt}} = \frac{F_* - (1 + K \cdot c)\left(A_* \overline{X}^r F^x + F_{fr}\right) + K \cdot c\left(X_* - A_* \overline{X}^r\right)}{1 + K \cdot c},$$

which is valid at a positive numerator. Otherwise $F_{0_{opt}}$ is equal to zero.

This dependency is confirmed by experimental dependencies of the optimum values F_0 on F^x presented in Fig.3.17 for a central stick (in the work there were not sufficiently complete experimental data to plot the similar dependency for the side stick).

As it is seen from Fig.3.15, 3.18 and the relation (3.12) an introduction of breakout force effects on the optimum values of control sensitivity characteristics according to the law presented in Fig. 3.18 for lateral channel.

3.3.3. Loading damping.

The role of this parameter is not sufficiently studied yet not only for a side stick but also for other control levers. The experiments showed that when a force of coulomb friction is small or absent, an introduction of certain values of side stick damping leads to an increase of piloting accuracy (Fig.3.19) and improvement of pilot ratings PR. Under the absence of loading damping of a side stick in ground and flight researches the pilots usually noticed the PIO tendency arising, especially in lateral channel.

The positive effect of a side stick damping on aircraft controllability in these cases is explained first of all by that it increases the damping of a system "side stick + arm", which are very small because of small proper damping of the muscles governing the movements of an arm, especially in lateral channel. As far as mentioned system is a part of "pilot — aircraft" system, an introduction of the damping reduces the oscillation tendency of the system as a whole and PIO tendency as well. Besides, due to the damping the pilot obtains the feedback of a stick displacement velocity that allows him to increase an accuracy of his control actions and reduce piloting errors. At last, side stick damping weakens the influence of aircraft construction vibrations and pilot's accidental actions on piloting.

In Fig.3.20 there is depicted the obtained area of the advisable for the side stick values of loading damping $F^{\dot{x}}$ depending on loading gradient F^x. It is seen from the data that optimum values $F^{\dot{x}}$ for a side stick depend weakly upon the loading gradient value F^x and can be considered to be equal to:

$$F^{\dot{x}} = 0.0015 - 0.002 \text{ kg / mm / s} \quad \text{for longitudinal channel,}$$

$$F^{\dot{x}} = 0.0015 - 0.002 \text{ kg / mm / s} \quad \text{for lateral control channel}$$

From Z−criterion, i.e. from the minimum of the function (3.11) along parameter $F^{\dot{x}}$, we obtain

$$F^{\dot{x}}_{opt} = \frac{1}{\omega_*}\sqrt{\left(\frac{F_* - F_0 - F_{fr} - 2Kc\left(A_*/|\overline{W}|\, X^r + c(F_0 + F_{fr}) - X_*\right)}{A_*/|\overline{W}| \cdot X^r\left(1 + 2Kc^2\, A_*/|\overline{W}| \cdot X^r\right)}\right)^2 - \left(F^x - m\omega_*^2\right)^2}.$$

It is seen from here that in decreasing the side stick loading gradient the loading damping optimum value increases. In this case the damping causes additional loading influence, therefore an introduction of damping coefficient effects positively on pilot ratings.

It should be mentioned that estimation of considered parameters of lever loading depends upon control sensitivity characteristics and a choice of them must be made considering the characteristics of particular aircraft.

3.4. Calculating definition of the optimum values of control sensitivity characteristics of unmanoeuvrable aircraft equipped with a side stick

3.4.1. The formulae for calculating.

The technique is expounded and grounded here which allows to calculate the optimum values of longitudinal (F_{n_z}, X_{n_z}) and lateral (F_p, X_p) control sensitivity characteristics of unmanoeuvrable aircraft equipped with a side stick for all flight regimes. In accordance with the above mentioned these characteristics can be defined proceeding from the A– and Z– criteria, if the magnitudes of the constants belonging to them are specified.

A type of the transfer function $\left|W_{c/X}\right|$ in longitudinal and lateral channels appearing in the A–criterion for choosing the optimum control sensitivity characteristics we will choose considering the interdependence of coordinates in every channel. For traditionally configured aircraft at deflection of control lever along longitudinal direction there appear simultaneously a pitch motion and a normal acceleration, and at deflection of control lever along the lateral direction there appear a roll and turn of flight trajectory. And the relationship between their intensities depends upon flight velocity V

$$q = \left(\frac{s}{n_{z_\alpha}} + \frac{g}{V}\right)\Delta n_z \tag{3.14}$$

$$\dot{\psi} = -\frac{g}{V}\phi = \frac{g}{V}\frac{1}{s}p \tag{3.15}$$

where s – Laplase operator; q, p, $\dot{\psi}$ – angular velocities of pitch, roll and turn of trajectory; Δn_z – the normal acceleration; g – gravity constant.

This leads to the fact that at low flight speeds the angular pitch velocities will have a strong impact on the choice of the characteristics of the longitudinal (F_{n_z}, X_{n_z}) and lateral (F_p, X_p) control sensitivity characteristics. And on the contrary, with an increase of the flight speed the role increases of the airplane's response in g–load and trajectory turn velocity. To account for this circumstance just as it was done for aircraft dynamic response according to C–criterion [5], as aircraft amplitude–frequency characteristics $|W_c|$, we will use a linear combination of the amplitude–frequency characteristics (AFC) on g–load $\left|W_{n_z}\right|$ and AFC on pitch velocity $|W_q|$ in longitudinal channel, and a linear combination of the amplitude–frequency characteristics on roll velocity $|W_p|$ and AFC on trajectory turn velocity $|W_{\dot{\psi}}|$ in lateral channel:

$$|W_c(j\omega)| = \left|W_{n_z}(j\omega)\right| + \frac{V_0}{g}\left|W_q(j\omega)\right|;$$

$$|W_c(j\omega)| = \left|W_p(j\omega)\right| + k\left|W_{\dot{\psi}}(j\omega)\right|,$$

where V_0 and k – the weight coefficients.

Taking into account these relations and (3.14), (3.15) the A–criterion assumes the following form:

For longitudinal channel

$$\left[\left(1+\frac{V_0}{n_{z_\alpha} g}\sqrt{\omega_*^2+\left(\frac{n_{z_\alpha} g}{V}\right)^2}\right)\left|W_{n_z}\left(j\omega_*, X_{n_z}^{opt}, \varsigma_{sp}, \omega_{sp}, \ldots\right)\right|\right]^{-1} = A_l\left(F^x, F_0, \ldots\right) \tag{3.16}$$

The values of the coefficients appearing herein V_0, ω_* are defined from the condition of the best correlation of the calculated and experimental data and are of the following values:

$$V_0 = 140\ {}^{m}\!/\!_{s}; \quad \omega_* = 0.7\ s^{-1}$$

The optimum value of parameter F_{n_z} can be defined from the relation

$$F_{n_z}^{opt} = F^x \cdot X_{n_z}^{opt}$$

In Fig.3.21 there is presented the dependence of the parameter A_l appearing in (3.16) upon gradient F^x, which was obtained at other side stick loading characteristics equal to zero. The parameter A_l depends upon not only F^x, but F_0 , $F^{\dot{x}}$, F_{fr} and can be defined by the relation (3.12) , where c=2.5 mm/kg , æ=1, F_*=1.5 kg, X_*=20 mm, A_* = 0.5.

For lateral channel

$$\left[\left(1+k\frac{g}{V}\frac{1}{\omega_*}\right)\left|W_p\left(j\omega_*, X_p^{opt}, \varsigma, \ldots\right)\right|\right] = A_r\left(F^x, F_0, \ldots\right), \tag{3.17}$$

where k = 14; ω_* = 1.25 s^{-1};

A_r – parameter the value of which can be determined according to the Fig.3.22 in dependence of F^x at other values of side stick loading characteristics equal to zero. Dependence of A upon not only F^x, F_0 , but F_{fr} , $F^{\dot{x}}$ is defined by the relation (3.12), where c =5 mm/kg, æ = 1, F_*=1.5 kg, X_*=20 mm, A_* = 7 ${}^{deg}\!/\!_{s}$.

The optimum control sensitivity characteristics in lateral channel F_p can be defined from the expression

$$F_p^{opt} = F^x \cdot X_p^{opt}$$

Thus, the relations (3.16), (3,17) allow us to define by calculation the optimum $F_{n_z}^{opt}$, $X_{n_z}^{opt}$, F_p^{opt} and X_p^{opt} having in mind:

- flight velocity V and value of parameter n_{z_α};
- values of F^x, F_0 and other loading characteristics;
- aircraft transfer functions from side stick displacements to normal acceleration W_{n_z} and angular roll velocity W_p. It should be mentioned that in this case the gain coefficient in the transfer functions must be presented through the characteristics X_{n_z} and X_p.

If there is known the AFC only of transfer functions W_{n_z} and W_p, or, to be more precise, only their values at characteristic frequencies ω_*, and the values X_{n_z} and X_p as well, at which the AFC were defined, then the optimum values $X_{n_z}^{opt}$, X_p^{opt} can be defined from the following relations:

$$X_{n_z}^{opt} = A_l\left(F^x, F_0, \ldots\right) \cdot \left\{1 + \frac{V_0}{n_{z_\alpha} g}\sqrt{\omega_*^2 + \left(\frac{n_{z_\alpha} g}{V}\right)^2}\right\}\left|W_{n_z}\left(j\omega_*, X_{n_z}\right)\right| X_{n_z}$$

$$X_p^{opt} = A_r\left(F^x, F_0 \ldots\right) \cdot \left(1 + k\frac{g}{V}\frac{1}{\omega_*}\right) \cdot \left|W_p\left(j\omega_*, X_p\right)\right| X_p$$

3.4.2. A comparison of experimental and calculated results.

To indicate the efficiency of stated technique and to define qualitatively the degree of dependence of optimum control sensitivity characteristics values upon aircraft dynamic performances, consider later on proceeding from calculated and experimental data the laws of influence of the principal longitudinal and lateral dynamic parameters on optimum values$F_{n_z}^{opt}$, $X_{n_z}^{opt}$, F_p^{opt}, X_p^{opt}.

Since the characteristics of the long–periodic motion have no noticable impact on the values of the amplitude frequency characteristics of transfer function W_c at frequencies of the order $\omega_* = 0.7\ s^{-1}$, then from the A–criterion (3.16) it follows that they do not influence the optimum values of the characteristics $F_{n_z}^{opt}$ and $X_{n_z}^{opt}$. This conclusion is confirmed by experimental data. In this connection we shall next consider the laws of the effects that only short–periodic motion parameters have on the optimum $F_{n_z}^{opt}$ and $X_{n_z}^{opt}$.

Usually the short–periodic aircraft motion is decribed by the transfer function of the following type:

$$W_{n_z/X} = \frac{\omega_{sp}^2 / X_{n_z}}{s^2 + 2\varsigma_{sp}\omega_{sp}s + \omega_{sp}^2} e^{-s\tau}$$

In this case from (3.16) we will get the following expression for the definition of the optimum values $F_{n_z}^{opt}$ and $X_{n_z}^{opt}$:

$$X_{n_z}^{opt} = -\omega_{sp}^2 \frac{1 + \frac{V_0}{n_{z_\alpha} g}\sqrt{\omega_*^2 + \left(\frac{n_{z_\alpha} g}{V}\right)^2}}{\sqrt{\left(\omega_{sp}^2 - \omega_*^2\right)^2 + \left(2\varsigma_{sp}\omega_{sp}\omega_*\right)^2}} A_l \qquad (3.18)$$

$$F_{n_z}^{opt} = F^x \cdot X_{n_z}^{opt}$$

It is seen from here that the optimum values $F_{n_z}^{opt}$ and $X_{n_z}^{opt}$ depend on the natural frequency ω_{sp} and damping $2\varsigma_{sp}\omega_{sp}$ of the short–periodic motion of the aircraft and also on the parameter n_{z_α} and the flight speed V.

Fig.3.23 represents the calculated and experimental dependencies of the optimum values $F_{n_z}^{opt}$on the natural frequency ω_{sp}. These and other data show that the optimum values $X_{n_z}^{opt}$, $F_{n_z}^{opt}$ are practically equal for the short–periodic frequencies within a range $1 \le \omega_{sp} \le \infty$ with a condition, that $\left(1 - 2\varsigma_{sp}^2\right)\omega_*^2/\omega_{sp}^2 \approx 0$ (for instance, at $\varsigma_{sp} = 0.7$). As

at $\omega_{sp} > 1$ the ratio $\omega_*/\omega_{sp} << 1$, then this becomes to be evident, if the expression (3.18) is to be made in Tailor series expansion on ω_*^2/ω_{sp}^2:

$$X_{n_z}^{opt} = \left[1 + \frac{V_0}{n_{z_\alpha} g}\sqrt{\omega_*^2 + \left(\frac{n_{z_\alpha} g}{V}\right)^2} \cdot \left(1 + \left(1 - 2\varsigma_{sp}^2\right)\frac{\omega_*^2}{\omega_{sp}^2} + \ldots\right)\right] A_1$$

With a decrease of the natural frequency ω_{sp}, starting from $\omega_{sp} = \omega_* = 0.7\ s^{-1}$, if $2\varsigma_{sp}\omega_{sp} = \text{const} > 0.7$, the optimum values $X_{n_z}^{opt}$, $F_{n_z}^{opt}$ decrease approximately in proportion:

$$X_{n_z}^{opt} \sim \omega_{sp}^2; \quad F_{n_z}^{opt} \sim \omega_{sp}^2$$

It can be mentioned, that for aircraft which have no automatics or have a low level of automatization of manual control loop, as it was on aircraft of previous generations, the condition is usually met $\omega_{sp} > 1\ s^{-1}$, and/or $\varsigma_{sp} = 0.7$ and, therefore, one should consider $X_{n_z}^{opt}$ and $F_{n_z}^{opt}$ to be independent on ω_{sp}. For modern aircraft with a small stability margin in the case of automatics failure this condition is not always met and, therefore, when considering the problems of flight safety providing it is necessary to account a dependence of the optimum values $X_{n_z}^{opt}$, $F_{n_z}^{opt}$ on ω_{sp}. For aircraft instable on normal acceleration, when $\omega_{sp}^2 < 0$, the traditional characteristics X_{n_z} and F_{n_z} make no sense at all, since in this case the steady value of g-load is absent. As a control sensitivity characteristics in this case the ratio can be used of controlling moment magnitude, presented in angular pitch accelerations, to the lever displacement or to the controlling force proceeding from the stepped deflection of a control lever at the first moment. The stated technique allows to estimate also the advisable magnitude of this control sensitivity characteristics.

With a decrease of damping (ς_{sp} or $2\varsigma_{sp}\omega_{sp}$) the optimum $X_{n_z}^{opt}$ and $F_{n_z}^{opt}$ increase. The extent of influence of damping on these values depend on the natural frequency value at following way: the less is ω_{sp}, the more is an influence of damping upon the optimum $X_{n_z}^{opt}$, $F_{n_z}^{opt}$. It is seen from Fig.3.24 and relation (3.18).

In Fig.3.25 there are presented the calculated and experimental dependencies of advisable values of X_{n_z}, F_{n_z} on values if the parameter n_{z_α}.

These and other data show that, starting from roughly $n_{z_\alpha} = 10$, a decrease of parameter n_{z_α} leads to an increase of advisable characteristics $|X_{n_z}|$, $|F_{n_z}|$. At values of $n_{z_\alpha} > 10$ the advisable characteristics X_{n_z}, F_{n_z} do not depend practically on values n_{z_α}. From the qualitative stand point this dependency is known. However, its quantitative differences for various cases did not have the sufficient explanation. The proposed technique makes it possible to solve this problem for different aircraft characteristics in quantitative respect as well.

As it follows from the A-criterion, the control sensitivity does not depend on time delay, that is confirmed by the experimental data presented in Fig.3.26.

Consider the optimum lateral control sensitivity characteristics F_p and X_p.

In practice the simplified transfer function on roll rate W_p is usually considered, which are determined by isolated roll motion,

$$W_p = \frac{1}{X_p}\frac{1}{\tau_1 s + 1}$$

In this case the optimum control sensitivity X_p is determined by the roll time constant τ_1.

For this case the total relation (3.17) for a calculation of the optimum values of F_p^{opt}, X_p^{opt} develops into the following form:

$$X_p^{opt} = \frac{1 + \frac{g}{V}\frac{1}{\omega_*}}{\sqrt{\tau_1^2 \omega_*^2 + 1}} A;$$

$$F_p^{opt} = F^x \cdot X_p^{opt}$$

It is seen from here and Fig.3.27, that with increasing the roll time constant from 0 to 1 s, the optimum values of X_p^{opt} remain to be approximately invariable, but then they sharply decrease in inverse ratio to the τ_1. All numerous experimental data in available publications confirm this dependency at least in qualitative respect.

Both calculated and experimental data show also that with a decrease of flight speed V at changing flight regimes from cruise to landing approach, the advisable force and displacements, i.e. F_p^{opt}, X_p^{opt} increase.

Finally note, that the stated technique of optimum control sensitivity estimation has an approximate character. Nevertheless, the presented results and an experience of its using show, that it accounts quite well the main factors influencing the choice of optimum control sensitivity characteristics. The technique can be used in a solution of the complicated multiparameter task of chosing the aircraft advisable stability and controllability characteristics in order to simplify its solution, narrow a volume of needed experimental investigations and, thus, reduce the terms and expenses for a development and flight tests of an airplane.

CONCLUSIONS

The results, obtained in the work, allow to draw the following conclusions:

1. New experimental results on the controlability of non–maneuver airplane, equipped with a side stick, in the wide range of airplane dynamic characteristics, the side stick loading characteristics and control sensitivity are obtained. The major laws of the dynamic characteristic influence upon airplane handling qualities are revealed.

2. The comparative analysis of controlability, provided by the side control stick and the conventional controls show, that in the standard flight conditions and a proper selection of controlability characteristics the side control stick provides the handling qualities similar to the ones, provided by the conventional controls. However, the problem of the side control stick advantages and disadvantages from the handling qualities point of view is not quite clear yet. Despite the fact, that pilots usually prefer control by means of the side stick, the accuracy of piloting in the longitudinal channel, as well as left–hand piloting in the lateral channel is somewhat worse, that the accuracy by means of a wheel. Emergency situations controlability by means of the side stick requires particular attention and further investigation. The expediency of the side control stick application must be estimated separately for each case and considering specific conditions.

3. The theoretical approach and controlability criteria for the optimum control sensitivity characteristics and various control levers loading characteristics, worked out earlier, have been developed further. The parameters, included by the criteria were specified and a calculation technique to select the characteristics was worked out. It was shown, that the calculation results both qualitatively and quantitatively conform to the available experimental data. The loading and control sensitivity characteristics calculation technique allow to considerably reduce the experimental investigations, and hence, reduce aircraft development terms and expenditures.

It is expedient to continue the investigation in order to specify the theoretical approach and the controlability criteria for different types of aircraft (maneuver airplanes, helicopters, etc.) and on this base create new controlability criteria for various controlability characteristics (including the dynamic ones) selection.

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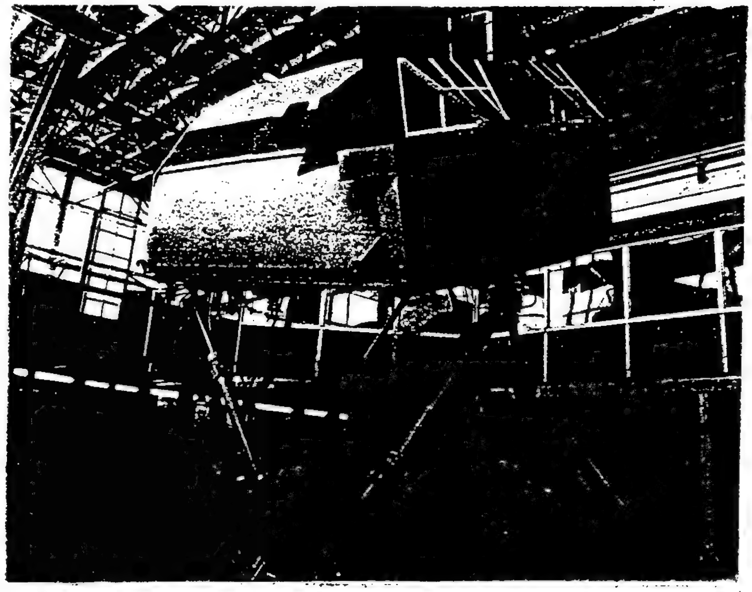


Fig.1.1. Flight Simulator FS-102

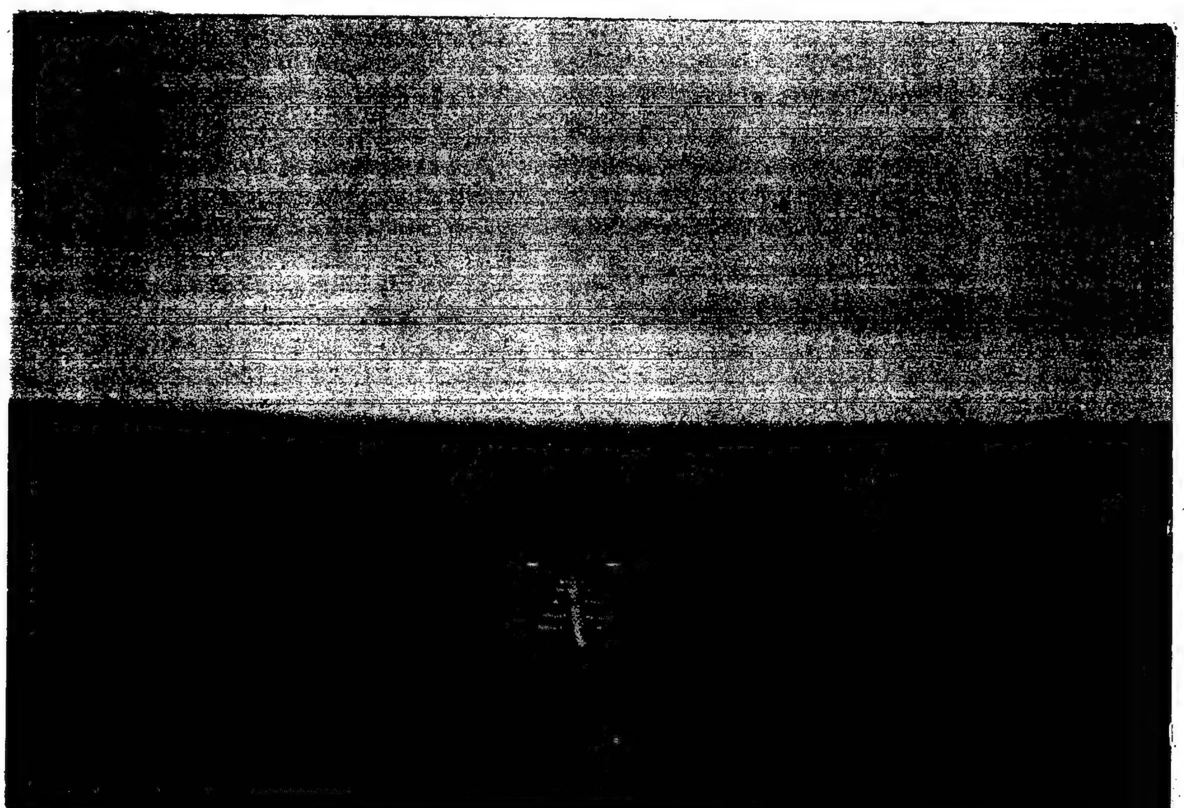


Fig 1.2 Computer generated image of the run way

Fig.1.3. Side stick RUS-D1

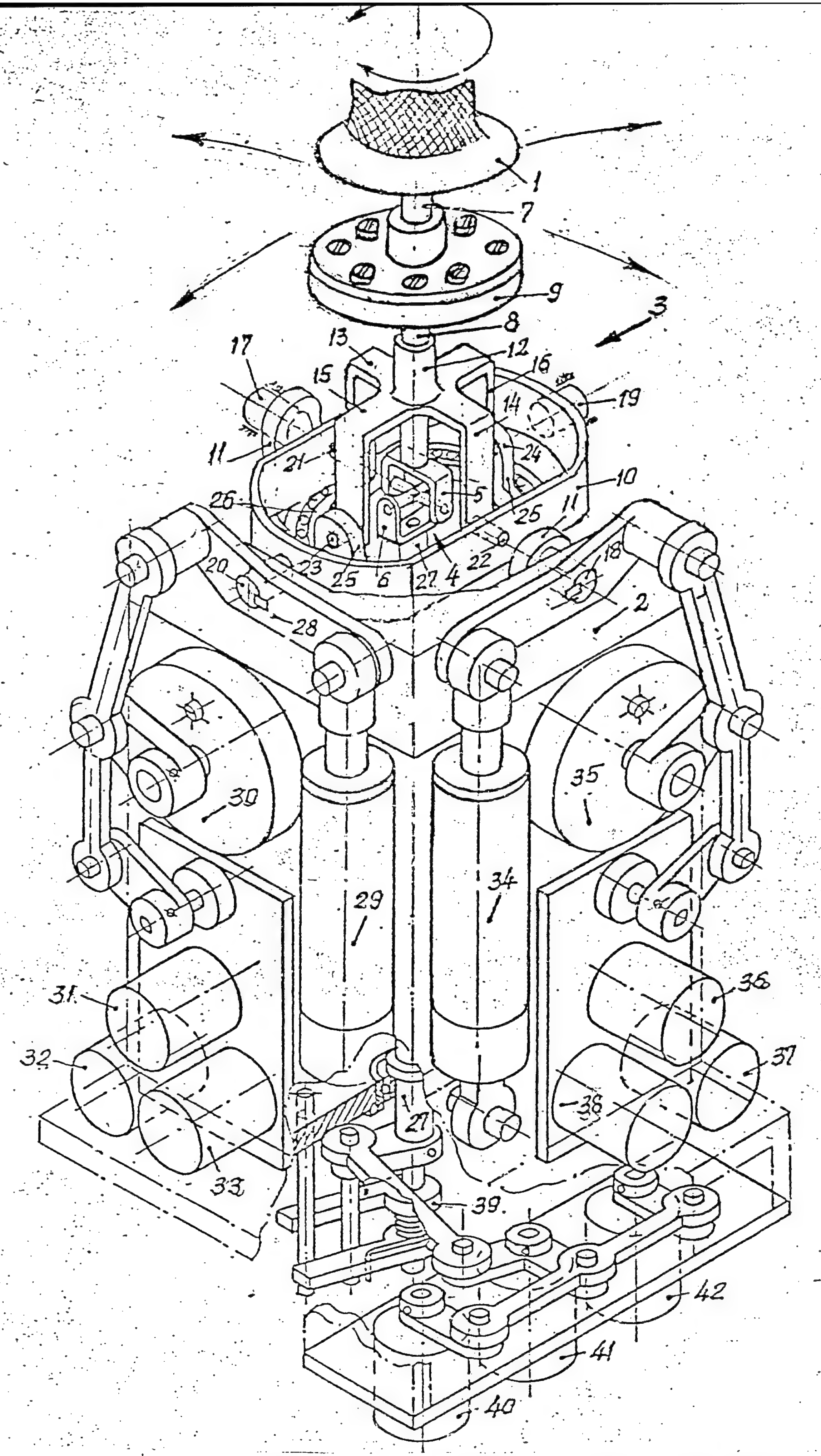


Fig.1.4. Constructive scheme of side stick RUS-D1

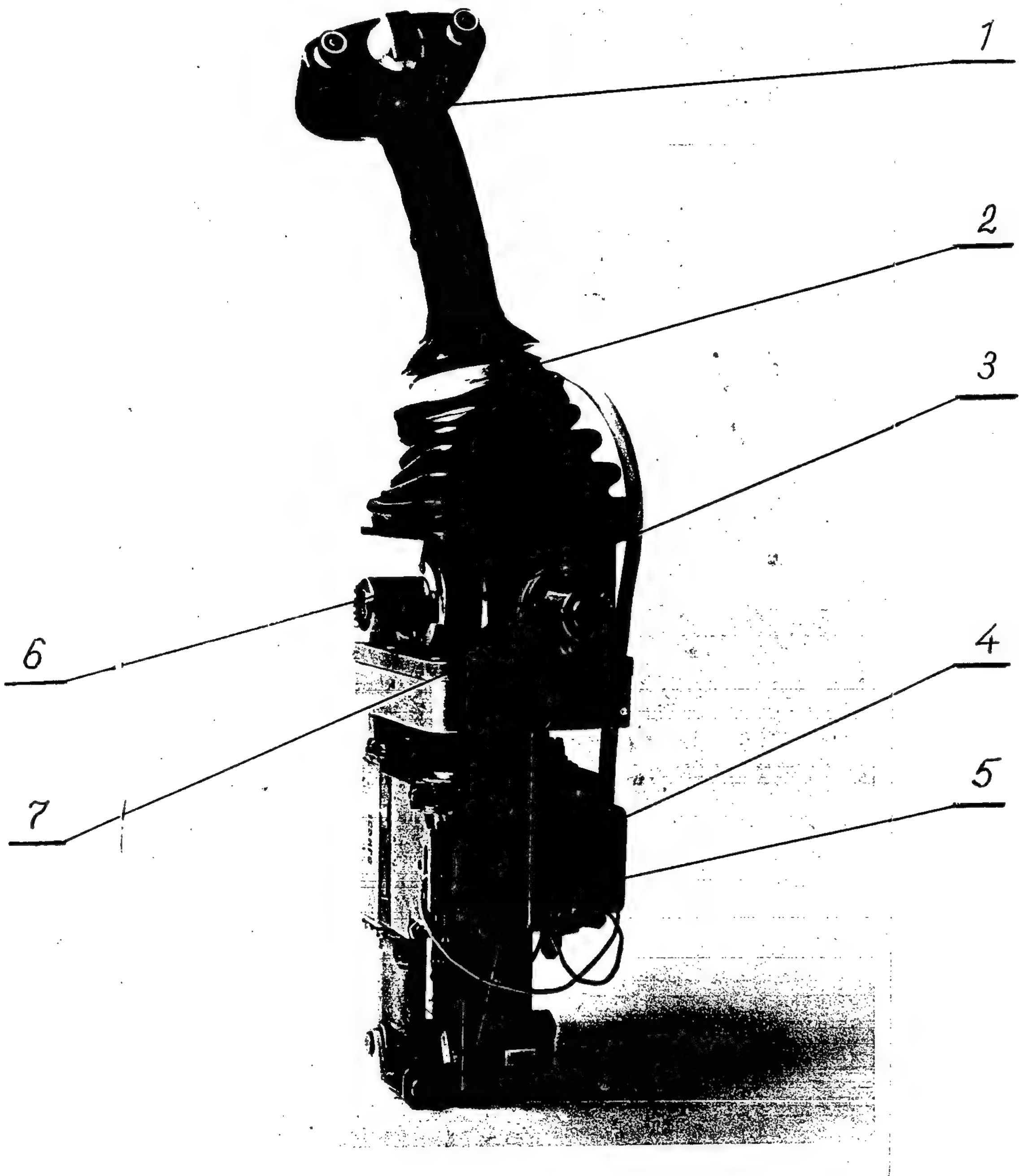
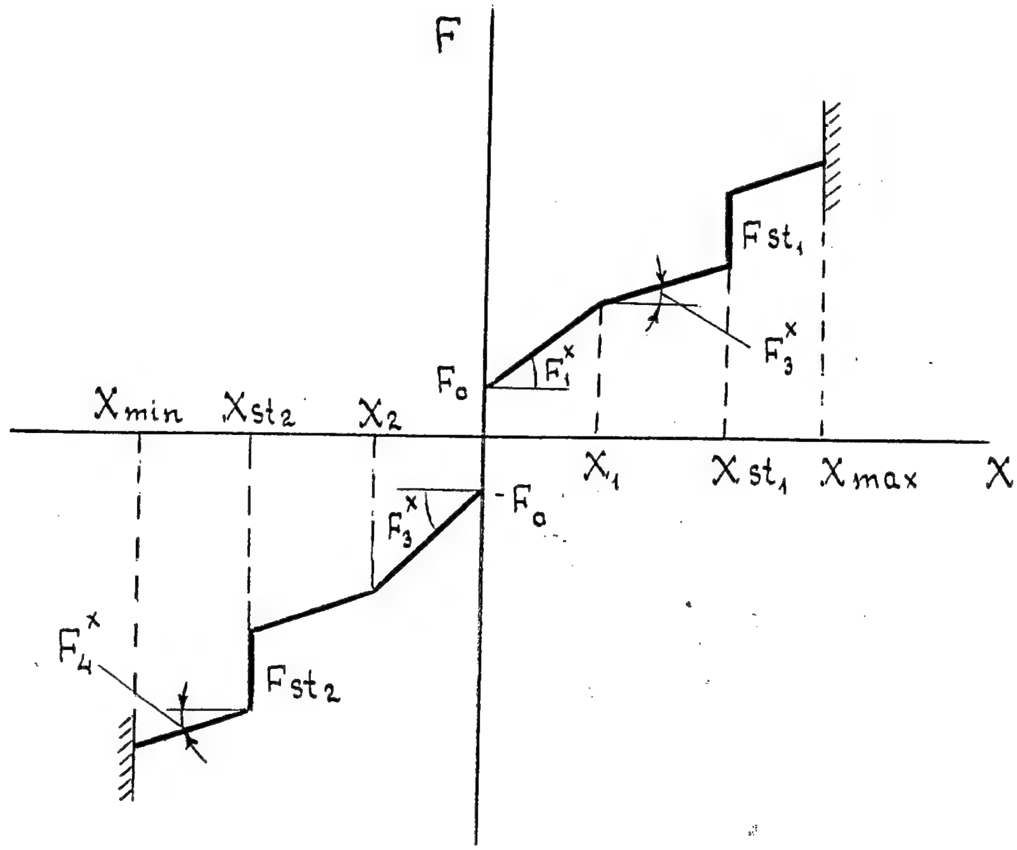


Fig.1.5. Side stick with electro-hydraulic loading system



Parameter	Ranges of varience pitch	roll
Breakout force Fo, kgf	0 -- 5	0 -- 3
Force/deflection gradient $F^x_{1,2}$, kgf/mm	0 - 0,5	0 - 0,3
Location of loading break point, X_1 , X_2 ; % X max	0 - 25	0 - 25
Loading force gradient after break point, $F^x_{3,4}$, kgf/mm	0 - 0,5	0 - 0,3
Force "step", F_{st} , kgf	0 - 10	-
Location of force "step" Xst, % X max	0 - 90	-

Fig.1.6. Typical loading law and the range of the loading parameters reproduced by the ECLS

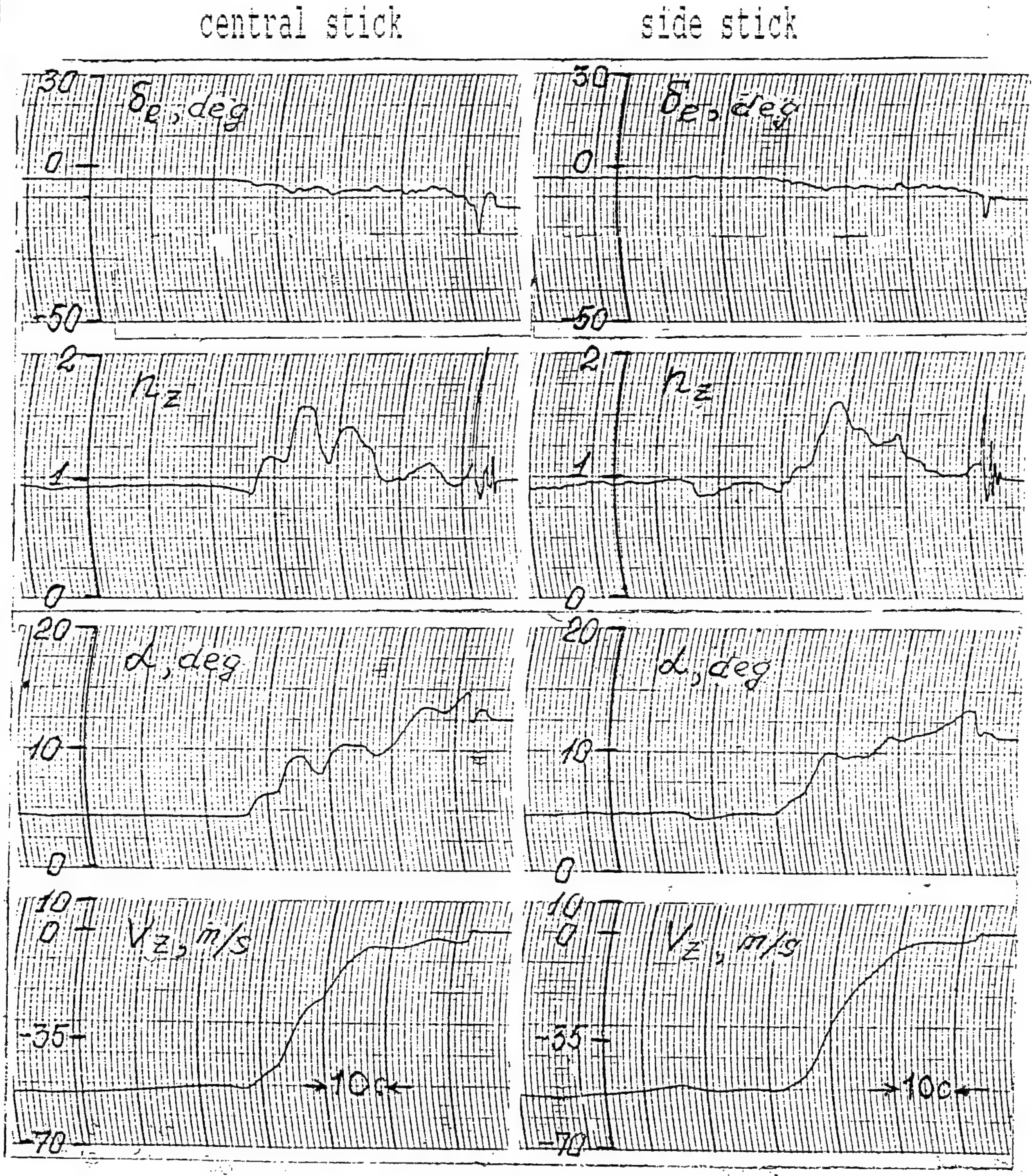


Fig.2.1. Piloting performances of a spacecraft at landing

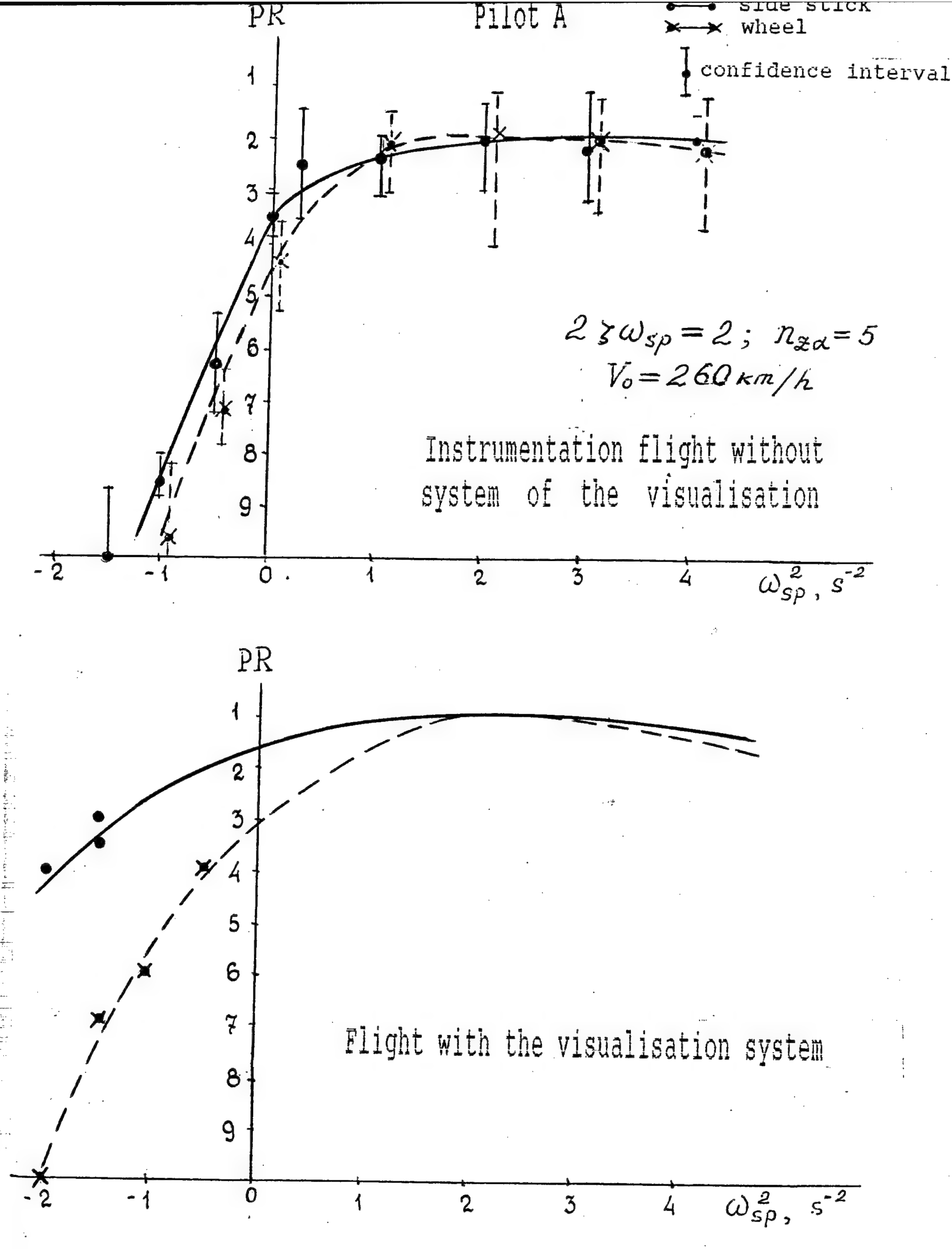


Fig.2.2. Pilot rating depending upon longitudinal short period frequency

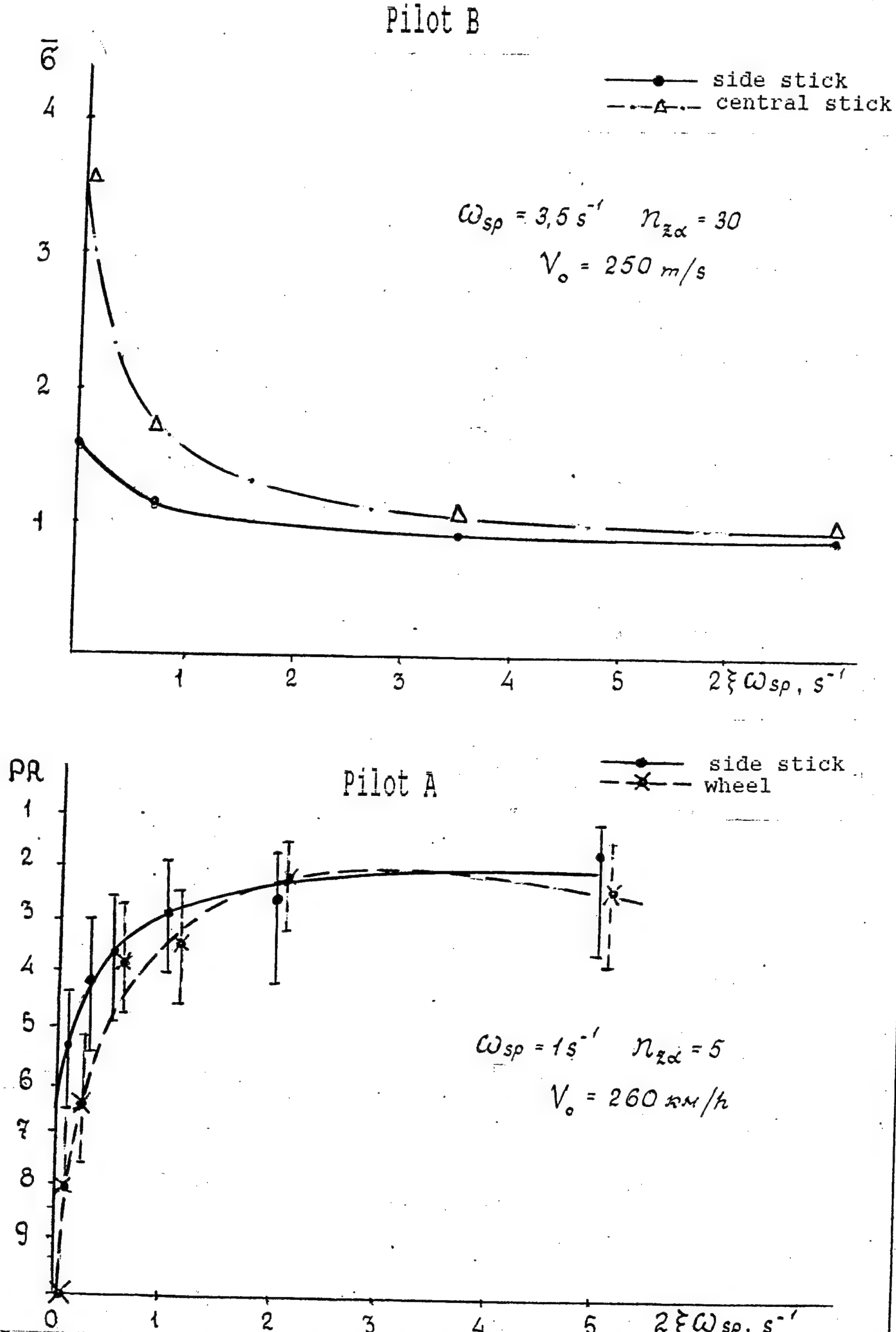


Fig.2.3. Pitch stabilisation error of the aircraft with the central and side stick and pilot rating of the aircraft with side stick and wheel in dependency of the longitudinal short-period movement damping

Pilot model: $W(p) = K e^{-p\tau}$

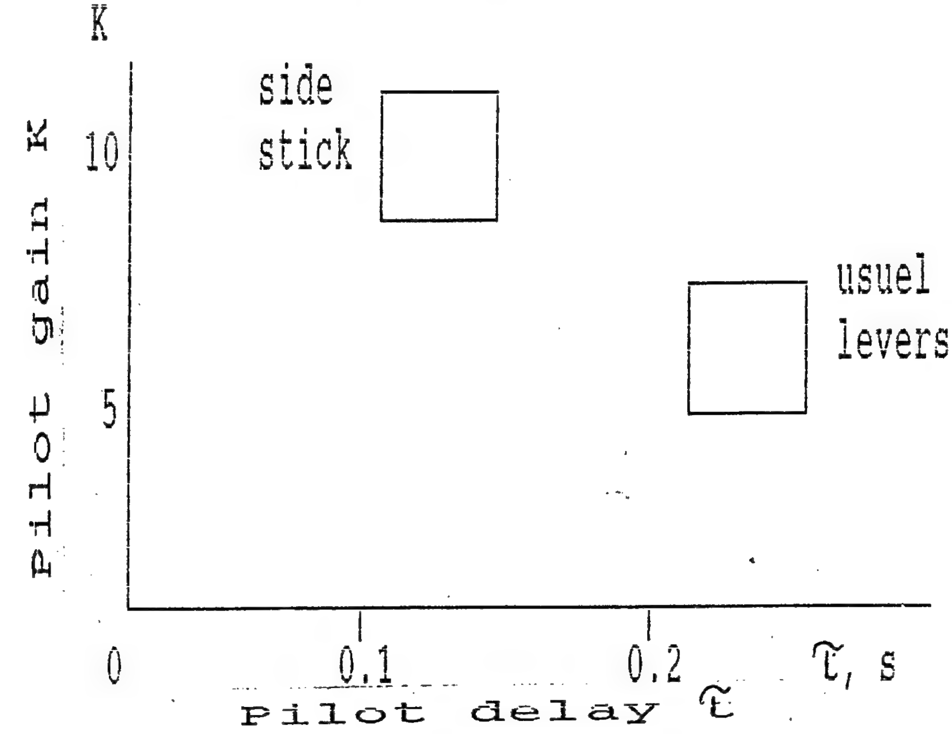


Fig.2.4. Lever type influencing on dynamic properties of a pilot

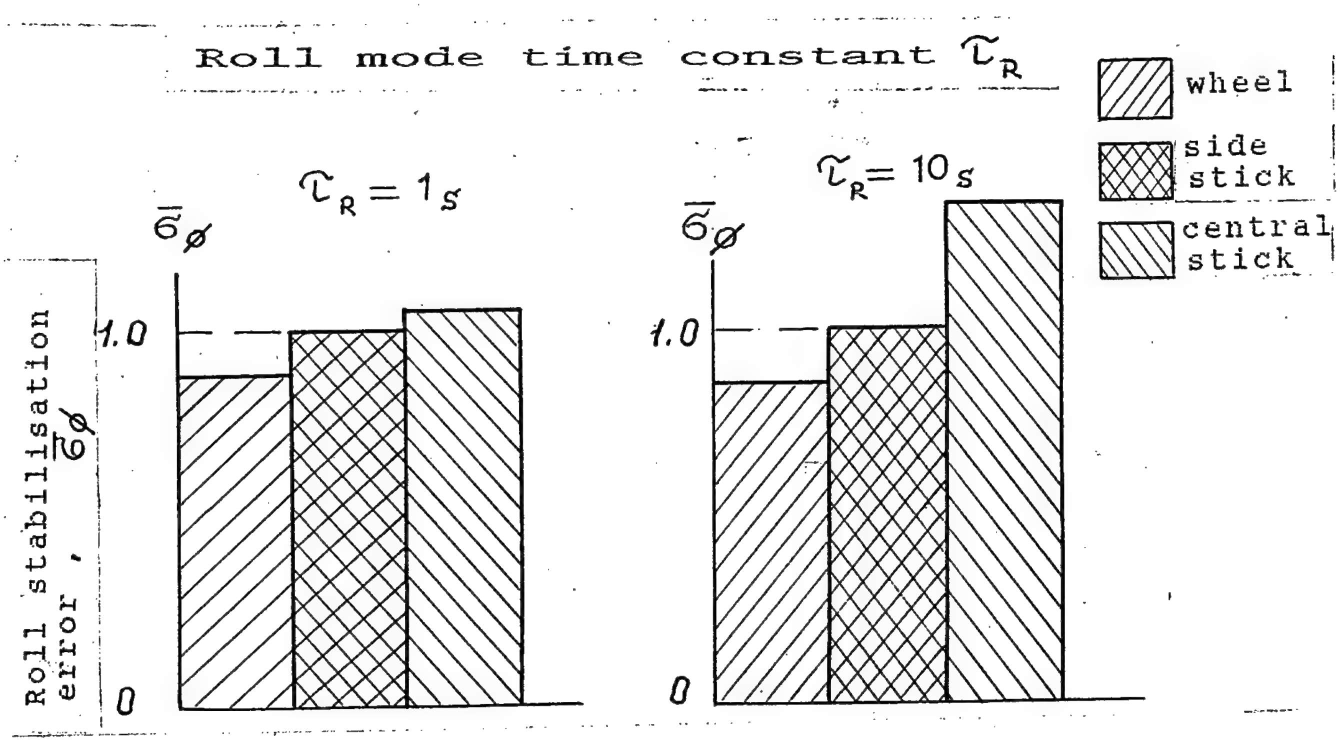
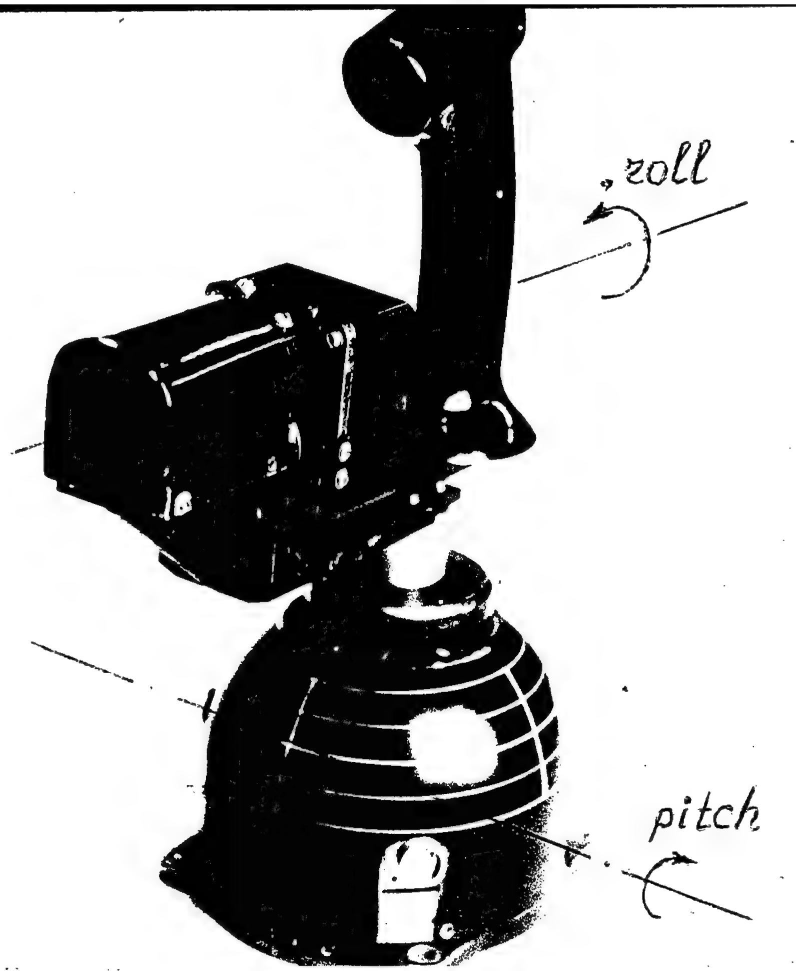


Fig.2.5. A comparison of roll stabilization accuracy while handling with the wheel, side stick and central stick (the data are common for 5 pilots)



The side stick of "grip" type

The side stick with of "bolt" type

Fig.2.6. The side sticks with uncrossing axes

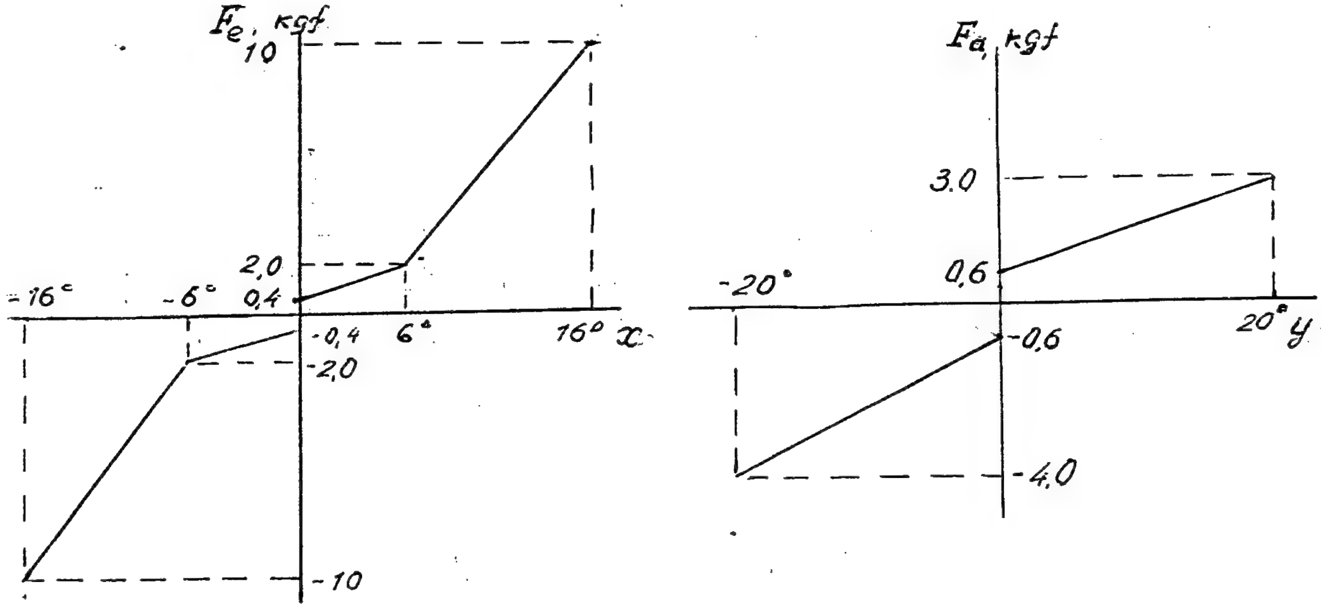


Fig.2.7. The loading characteristics of A-320 side stick

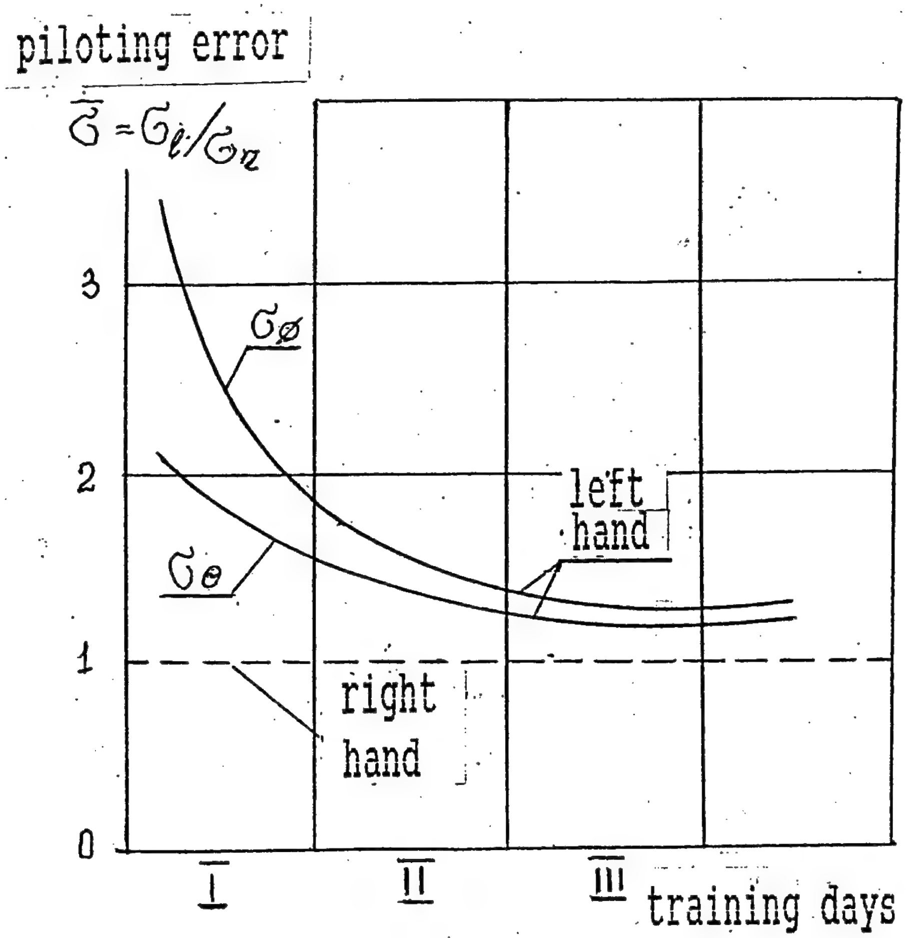


Fig.2.8. Left hand piloting accuracy of pilot-righties.

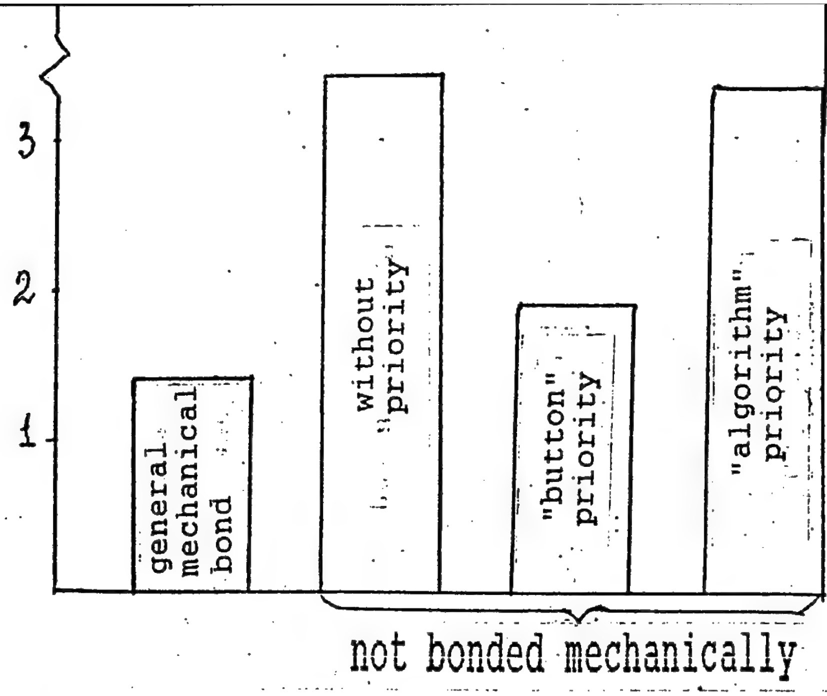


Fig.2.9. Pilot rating of different methods of two side sticks interactions (Ref.6)

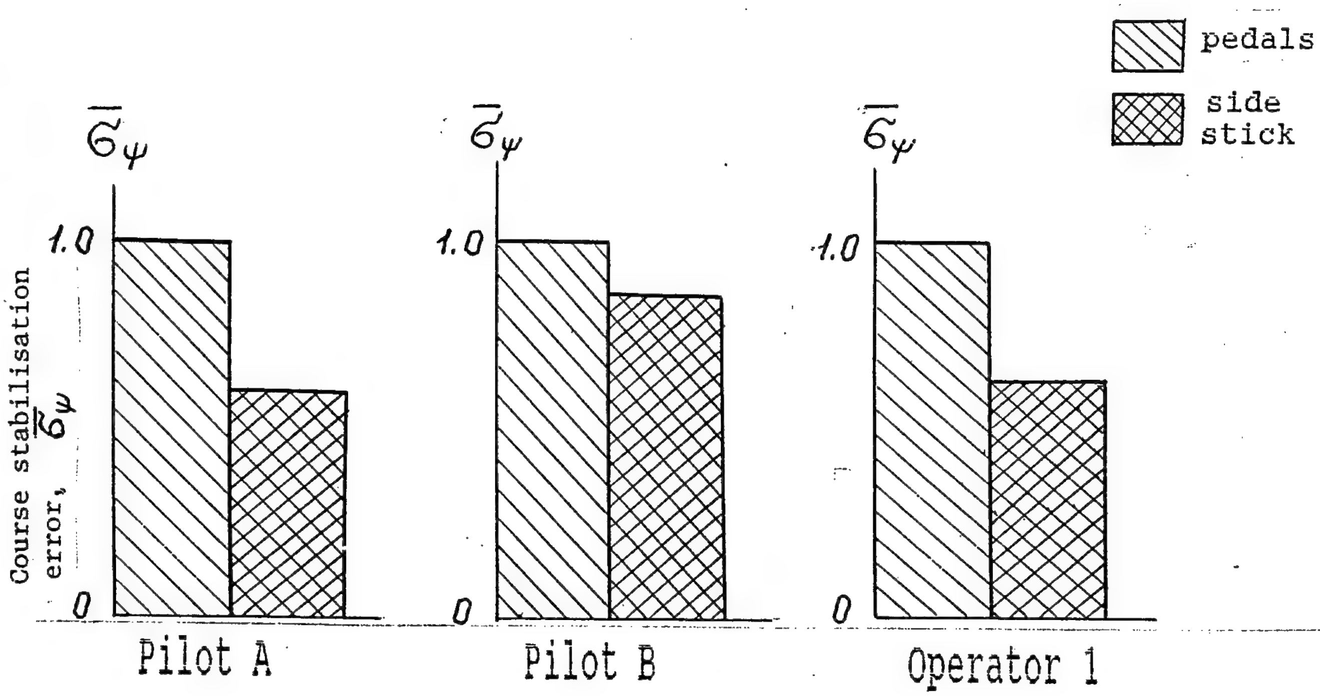


Fig.2.10. A comparison of yaw stabilization accuracy while handling with the side stick and pedals

Total lateral motion (roll+yaw)

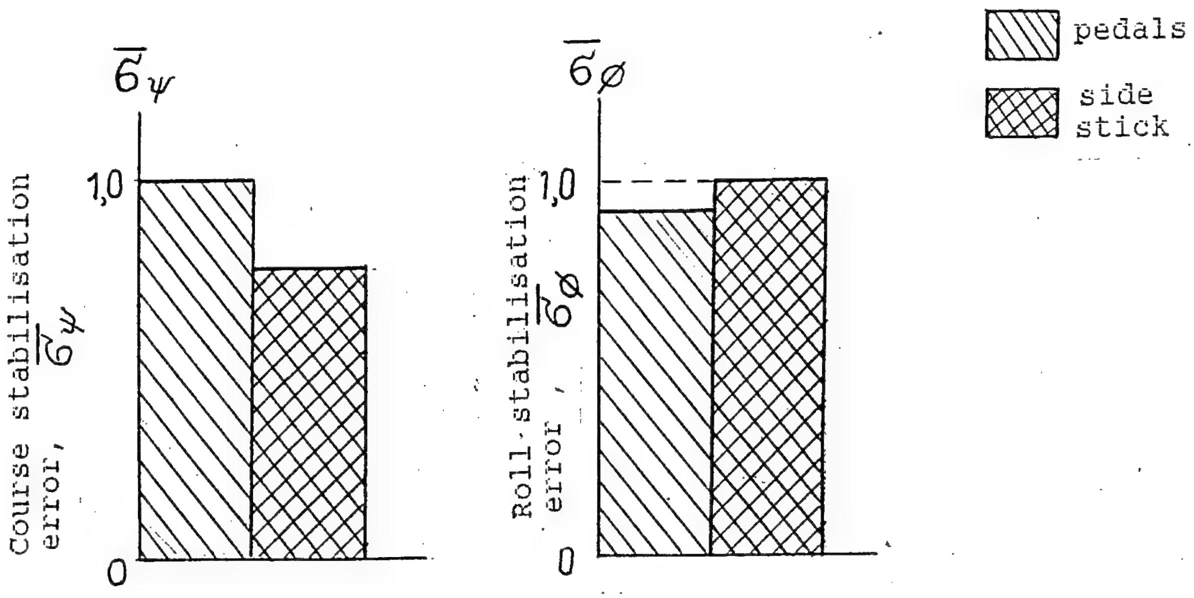


Fig.2.11. A comparison of roll and yaw stabilization accuracy while handling with the side stick and pedals (the data are common for 3 pilots)

Spatial motion (pitch+roll+yaw)

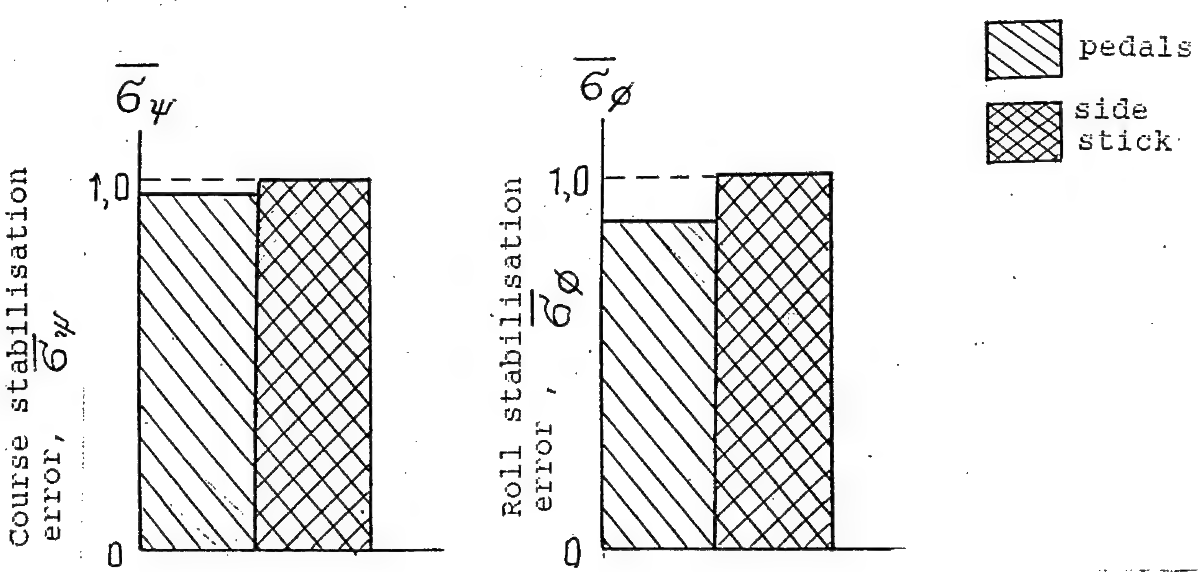


Fig.2.12. A comparison of roll and yaw stabilisation accuracy while handling with the side stick and pedals at landing approach (the data are common for 3 pilots)

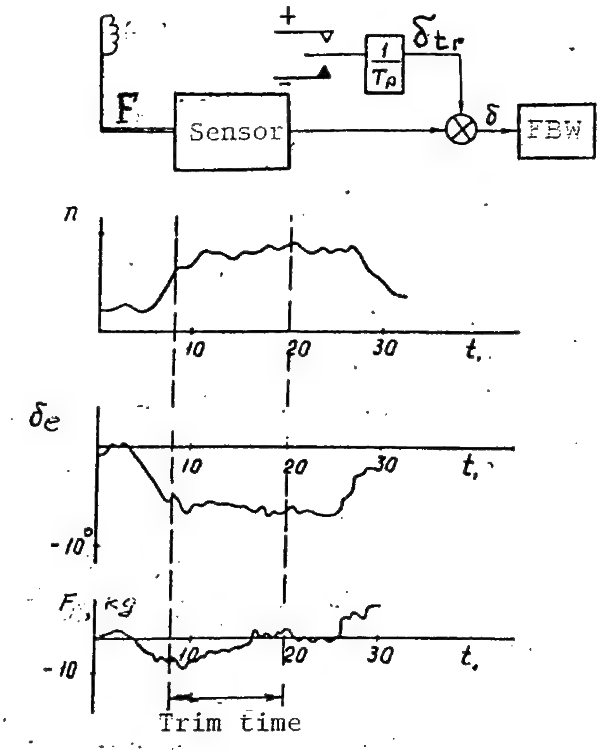


Fig.2.13. Manual electrical force trimming of a side stick

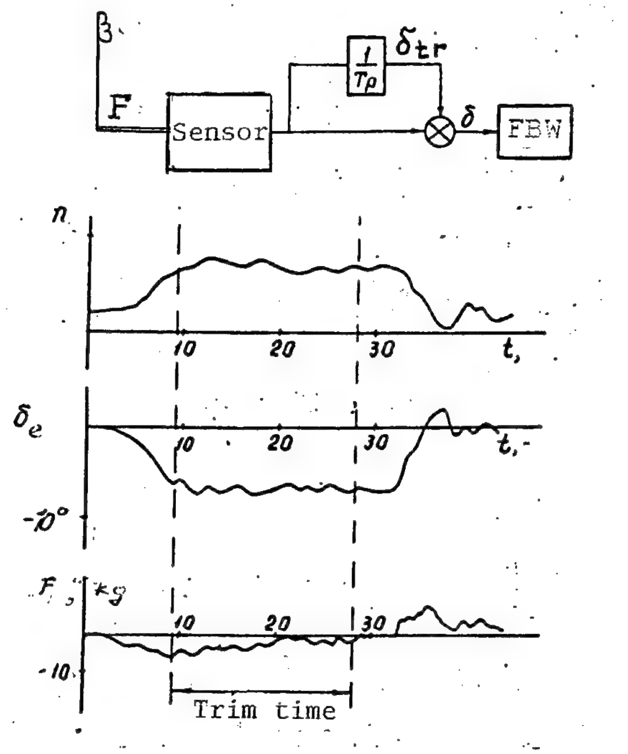


Fig.2.14. Semi-automatic electrical force trimming of a side stick

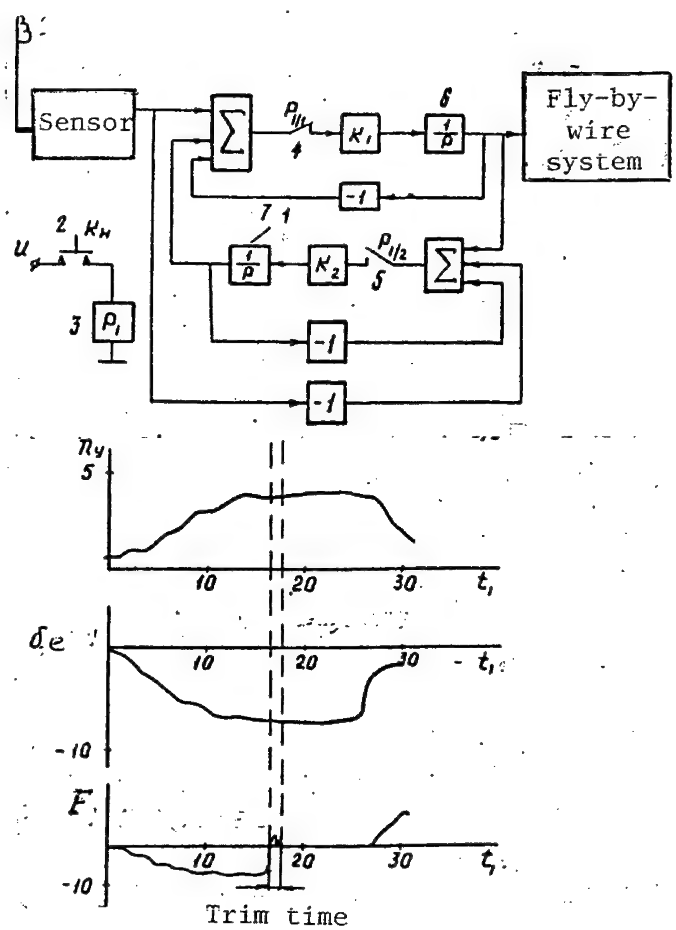


Fig.2.15. Scheme of a "fast" force trimming of a side stick

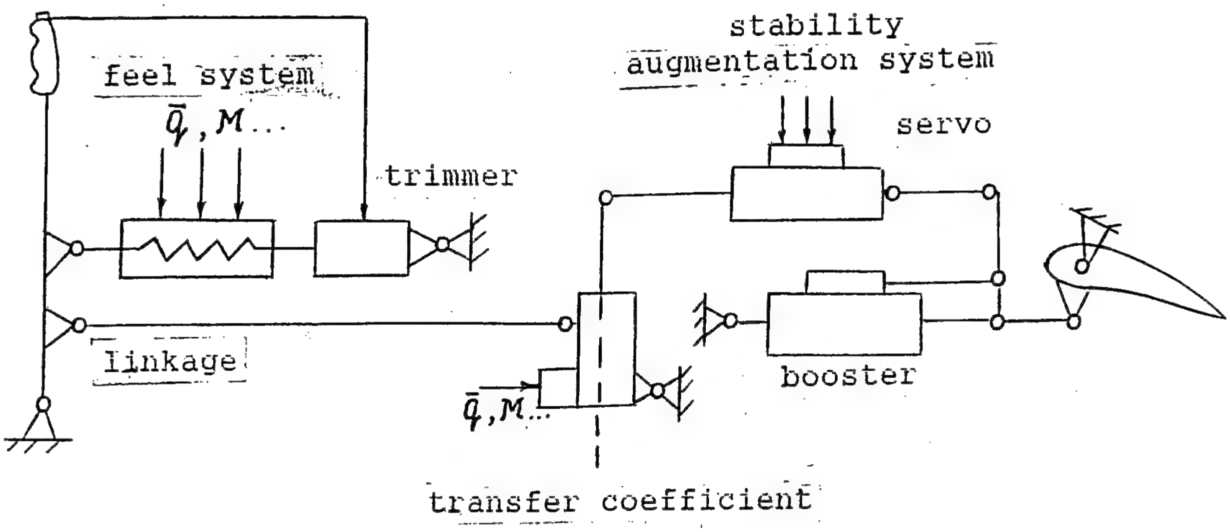


Fig.3.1. Aspects influencing the aircraft lever loading

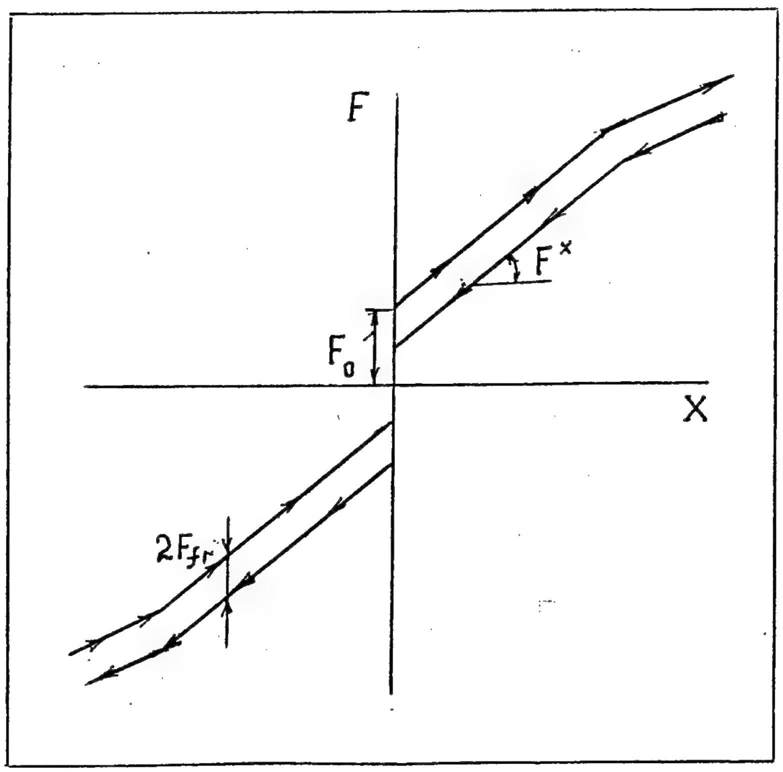
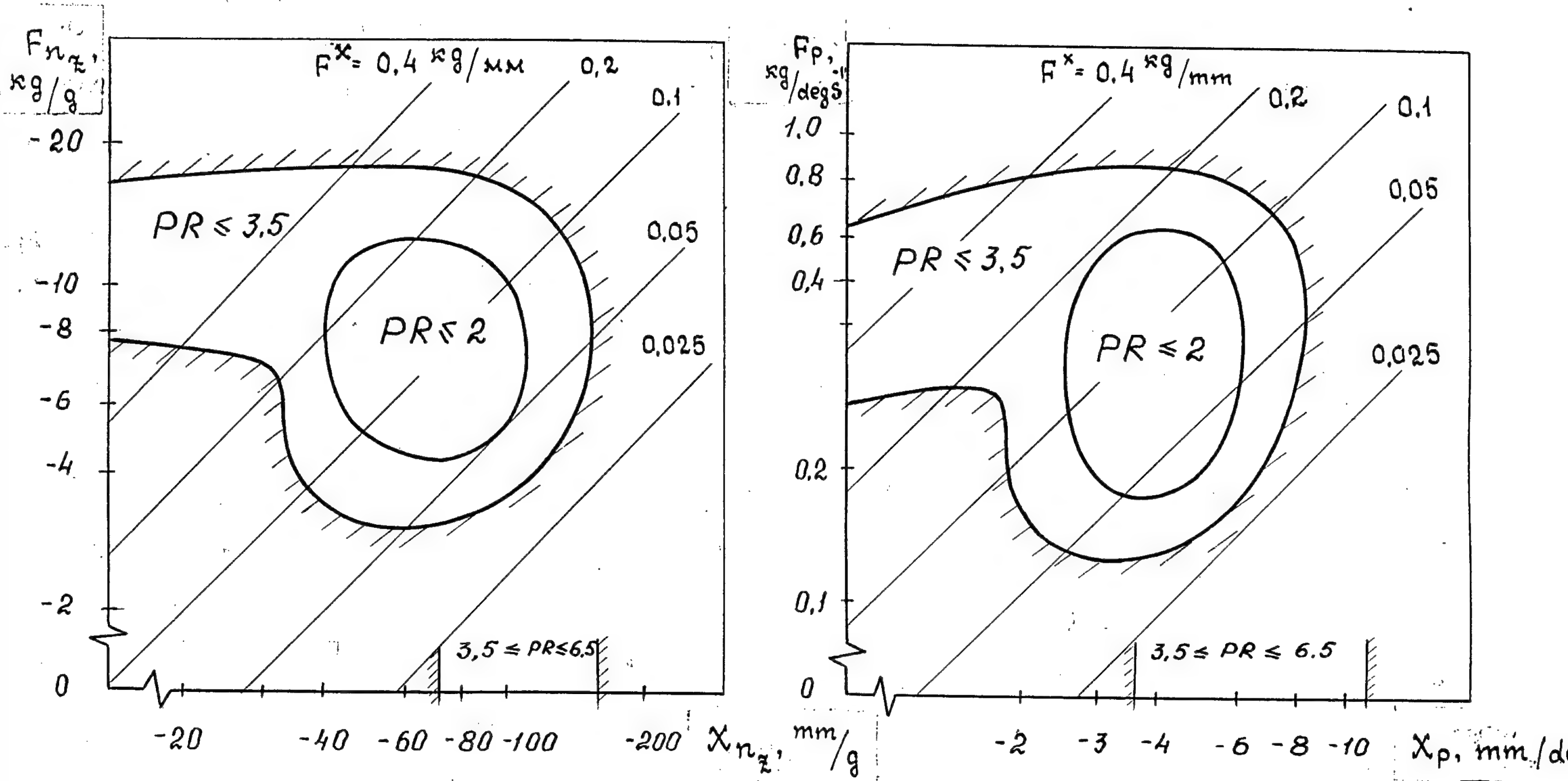


Fig.3.2. Static characteristics of lever loading



a) Longitudinal channel

b) Lateral channel

Fig.3.3. Pilot ratings regions in plane of the control sensitivity characteristics of side stick aircraft

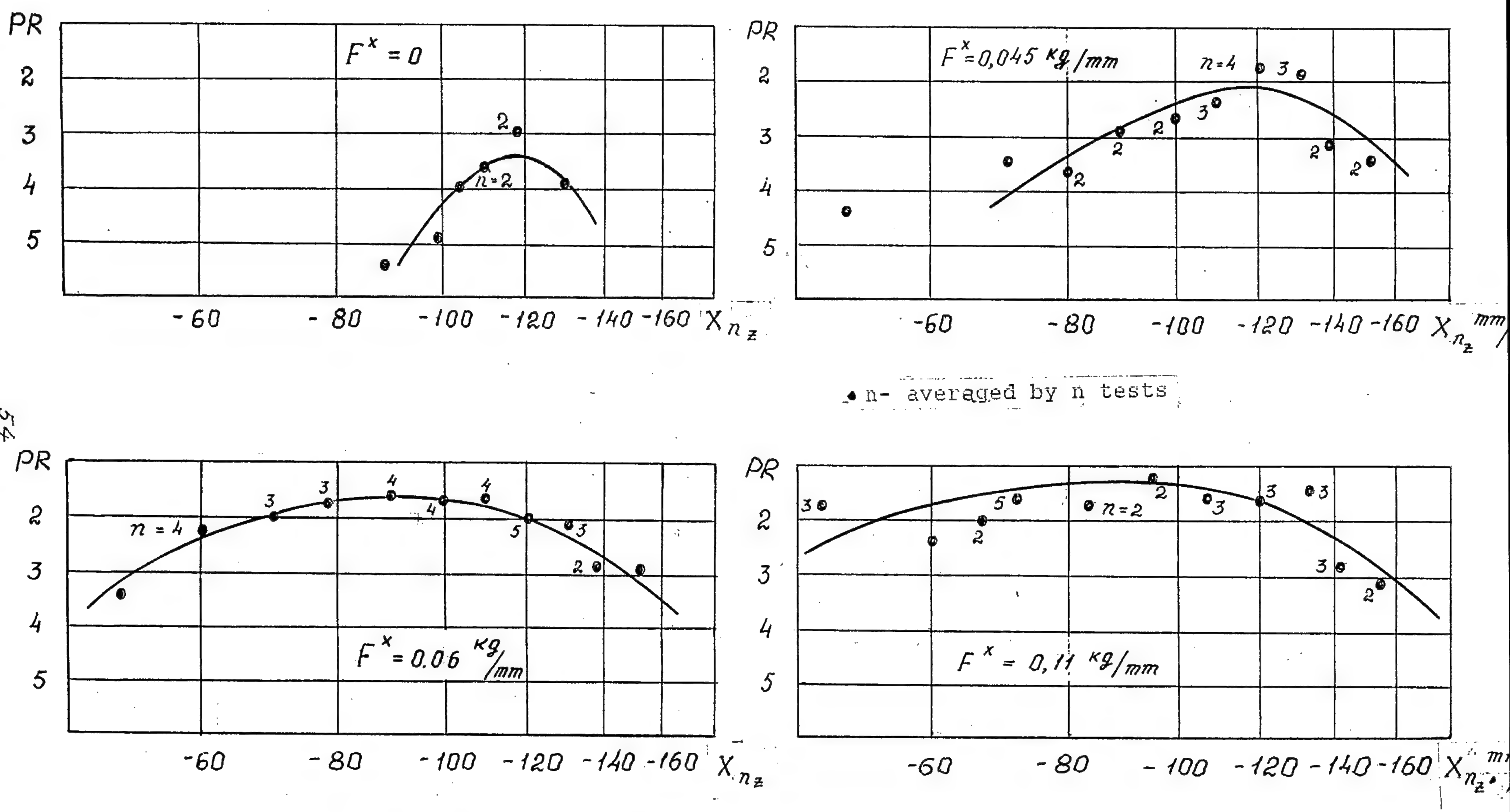


Fig.3.4. Longitudinal control sensitivity and side stick loading characteristics influencing the pilot ratings

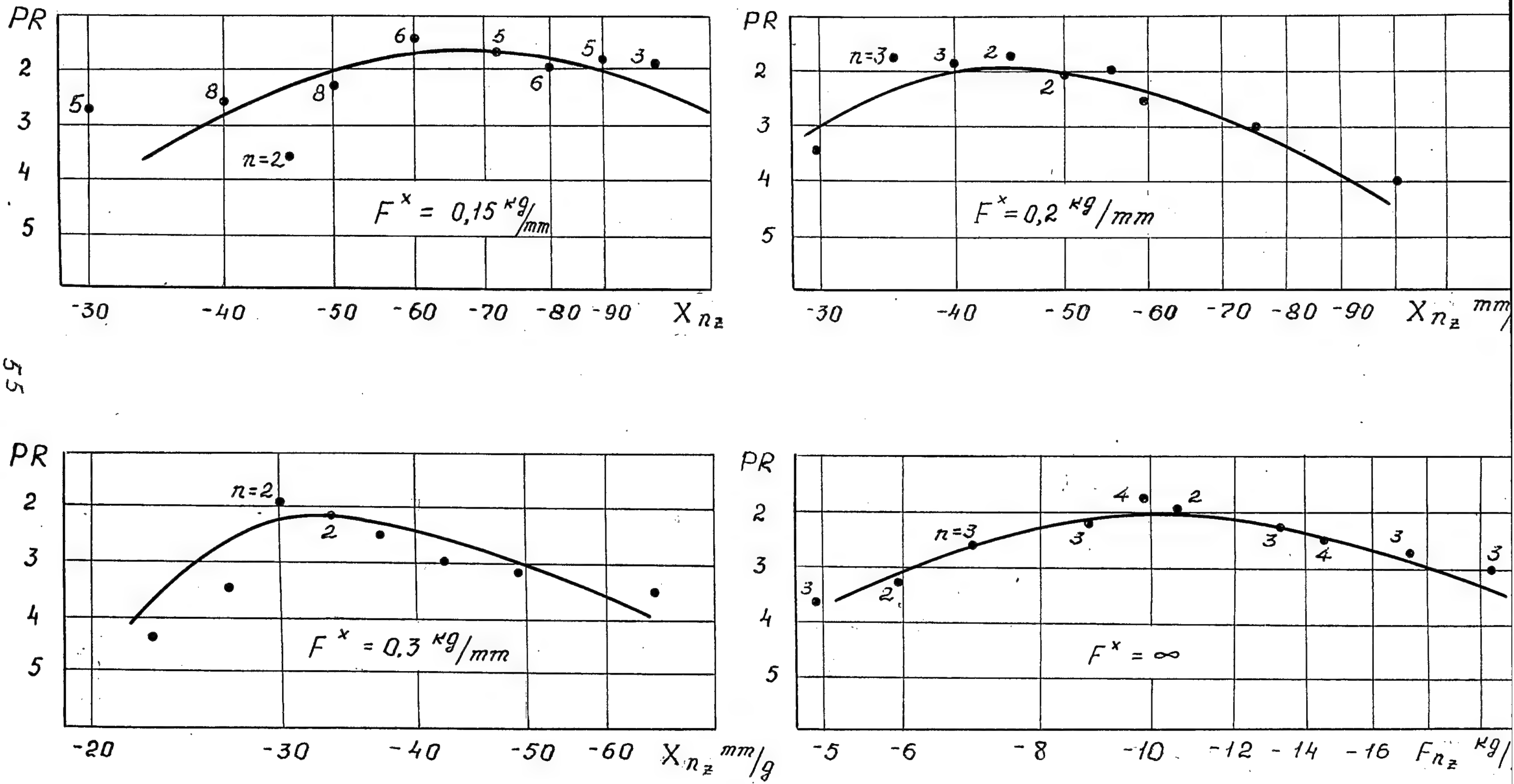


Fig.3.4. (continuation)

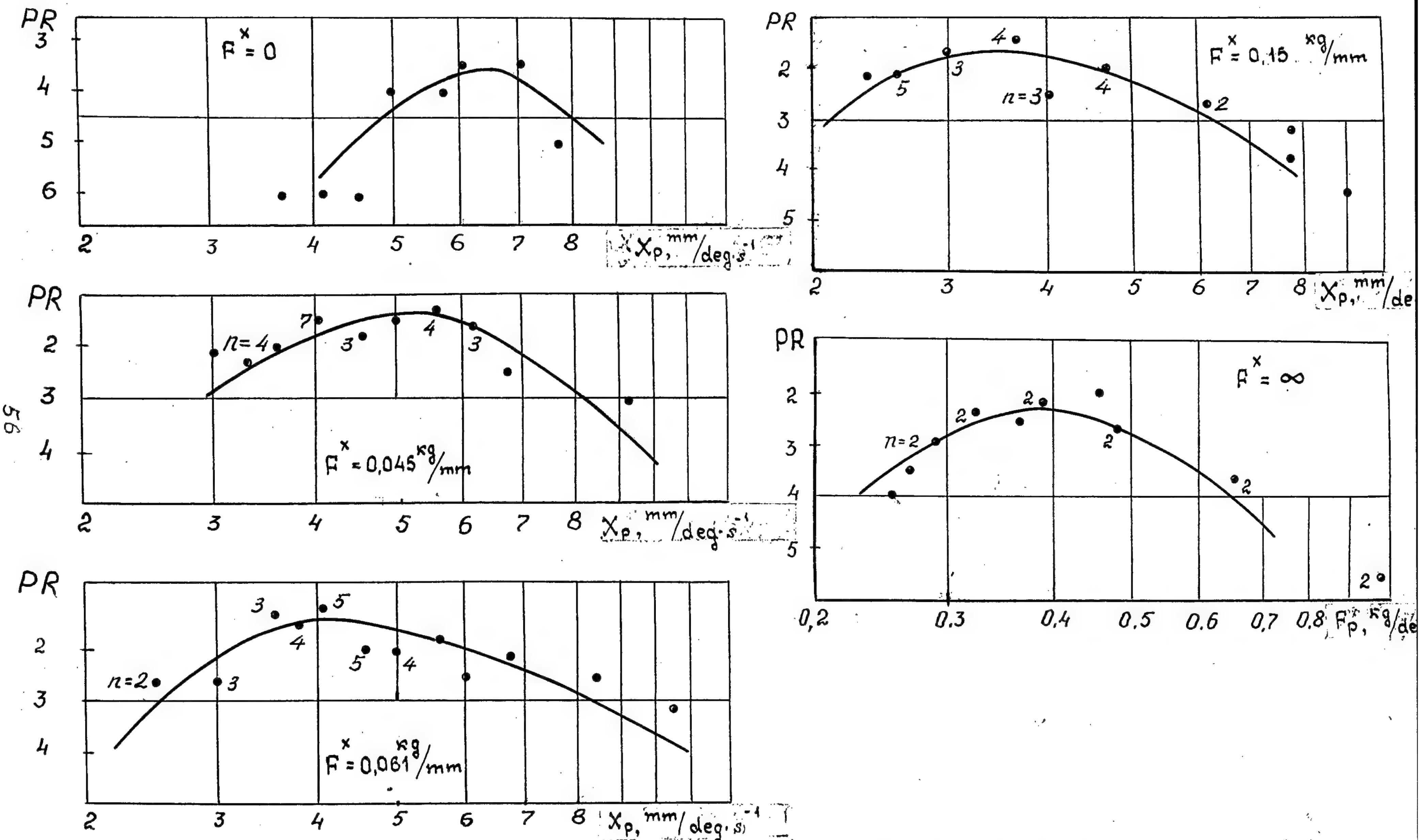


Fig.3.5. Lateral control sensitivity and side stick loading influencing the pilot ratings

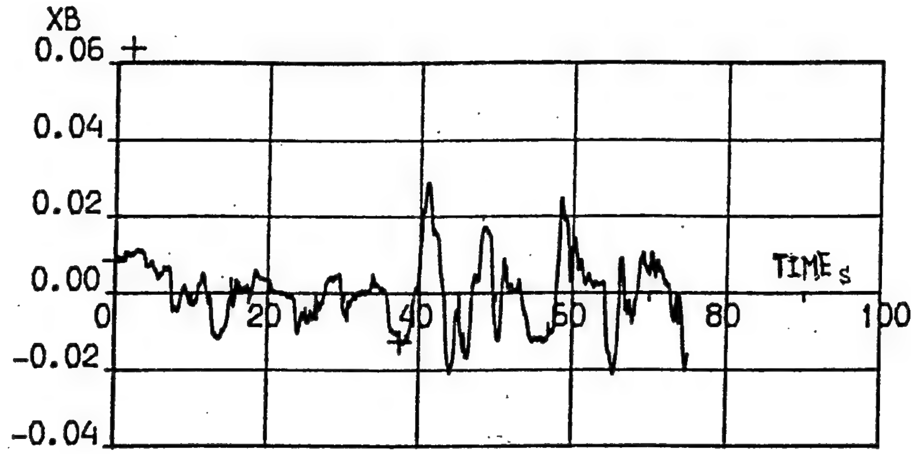


Fig.3.6. Deflections of control lever at estimating the control sensitivity

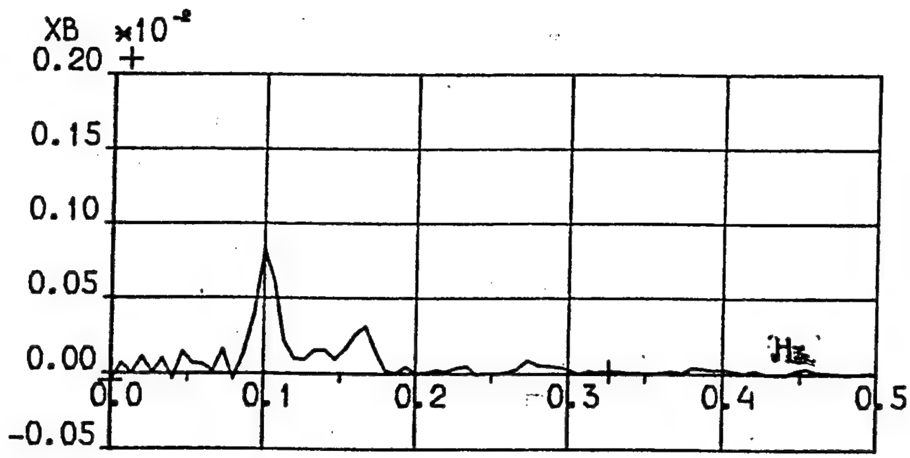


Fig.3.7. Spectral density of presented lever deflections

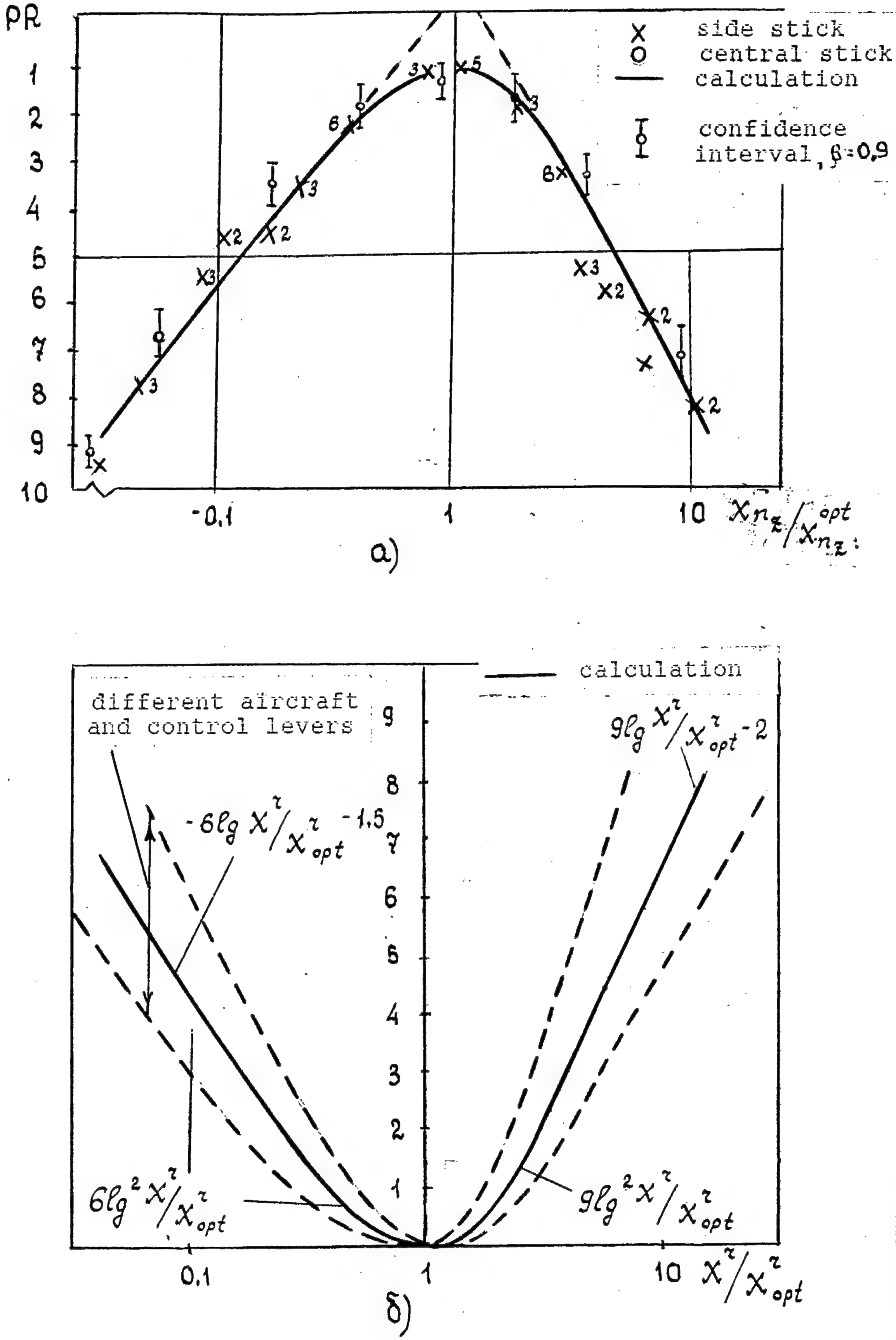


Fig.3.8. Pilot ratings worsening at deviation of control sensitivity characteristics from their optimum values

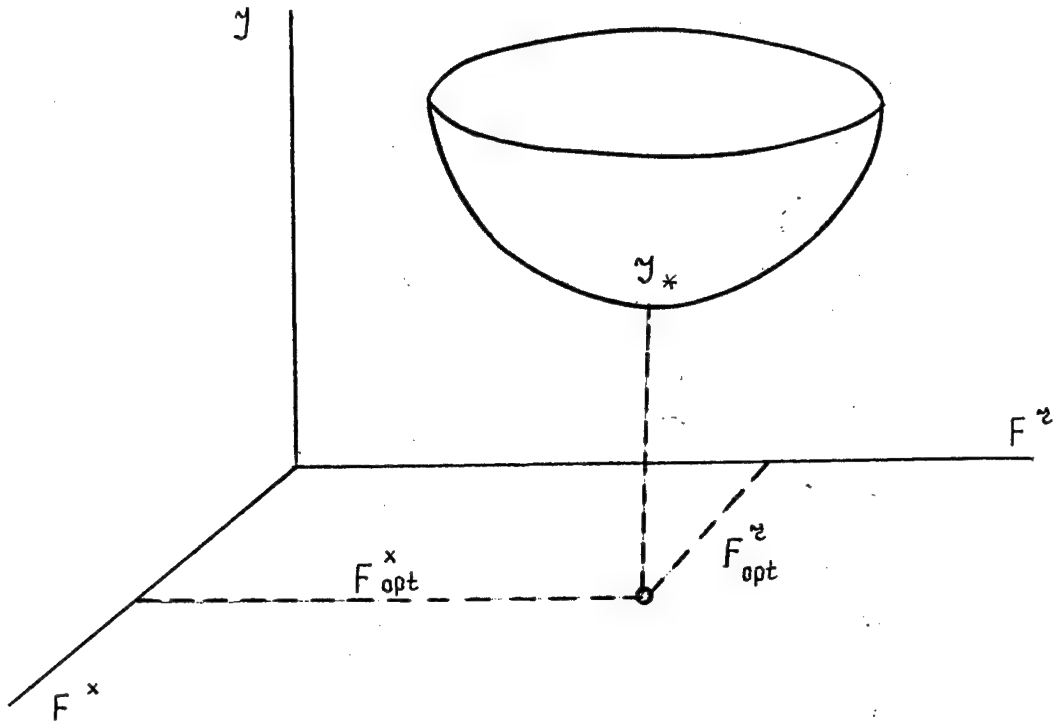


Fig.3.9.

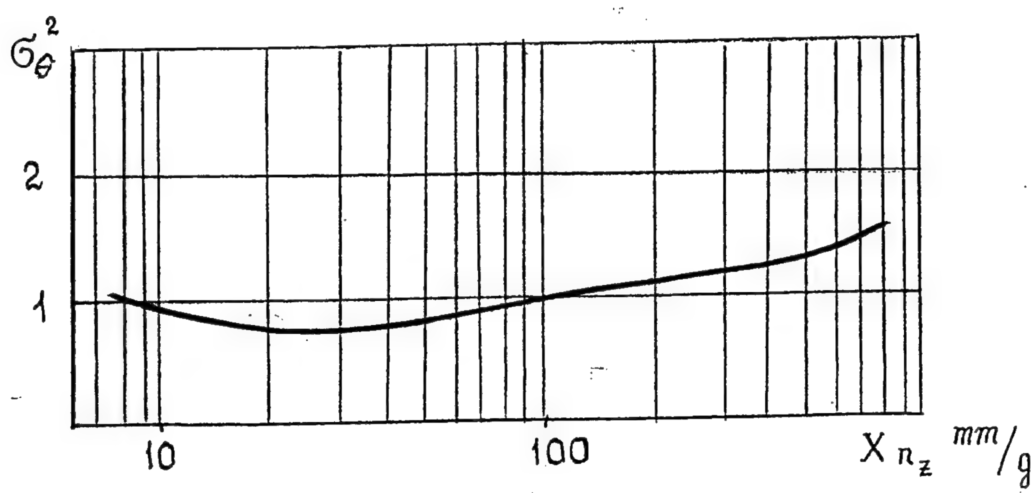


Fig.3.10. Dependence of pitch stabilization error dispersion on control sensitivity [11].

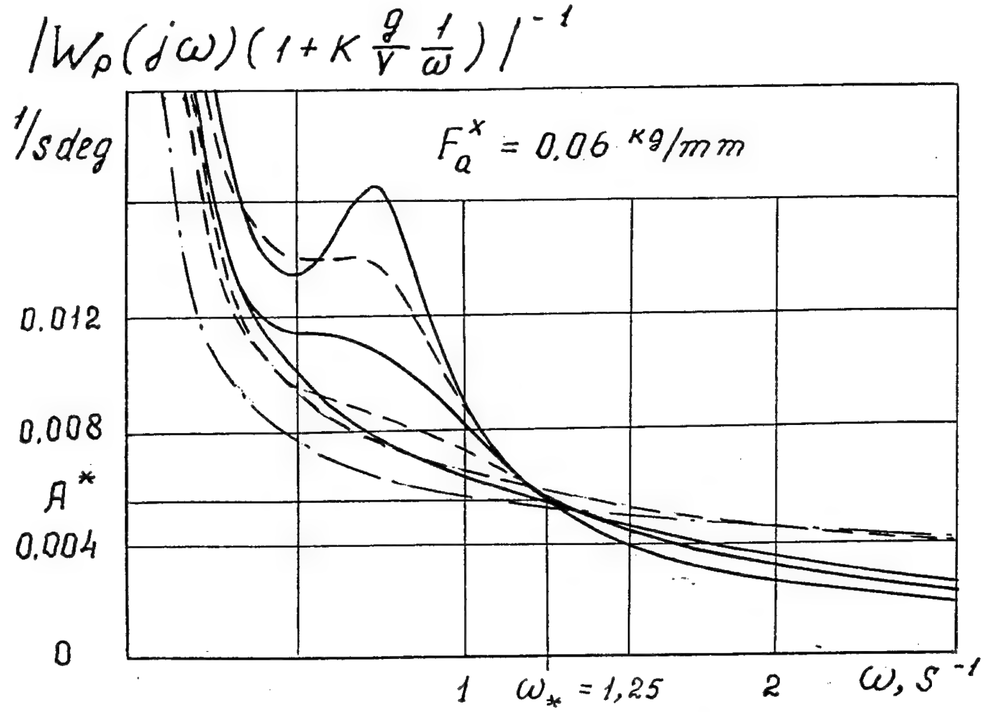


Fig.3.11. Aircraft amplitude-frequency characteristics at optimum control sensitivity.

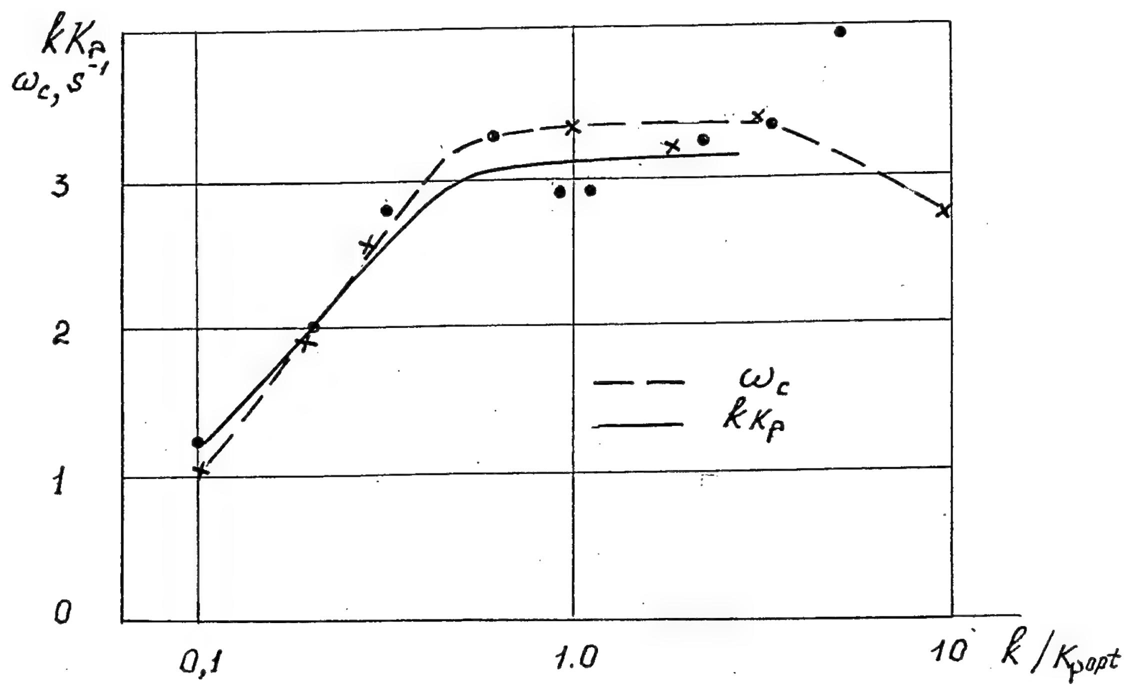


Fig.3.12. Dependences of the total gain coefficient kK and cut-off frequency of "pilot-aircraft" system on control sensitivity.

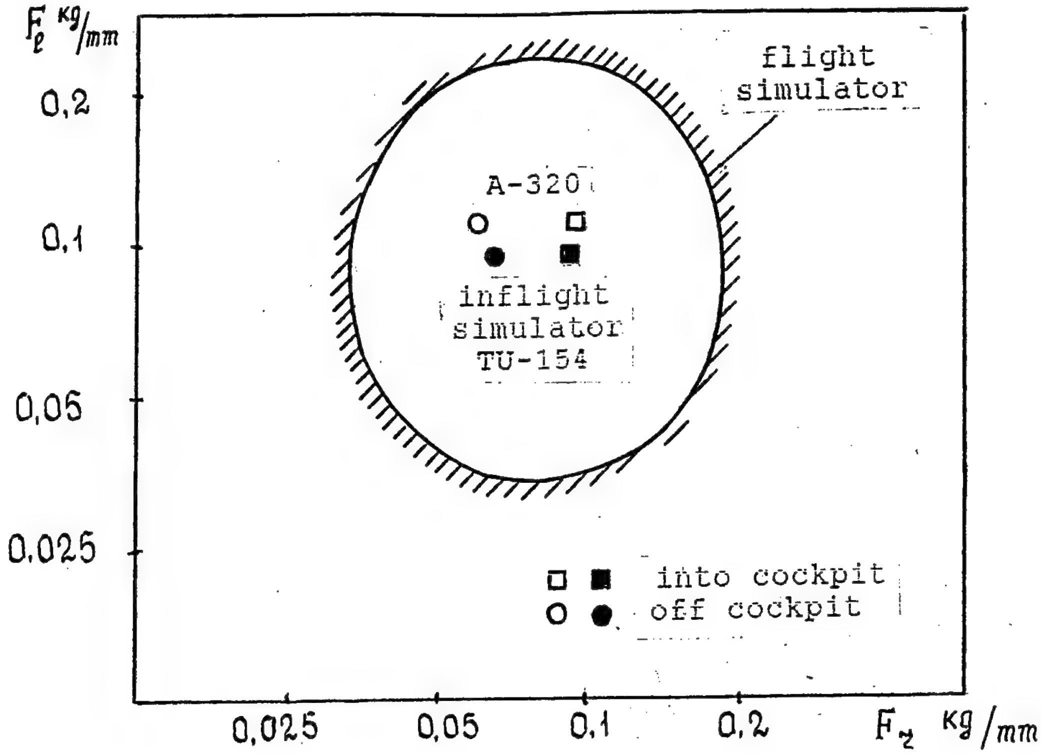


Fig.3.13. Optimal values of the side stick gradient.

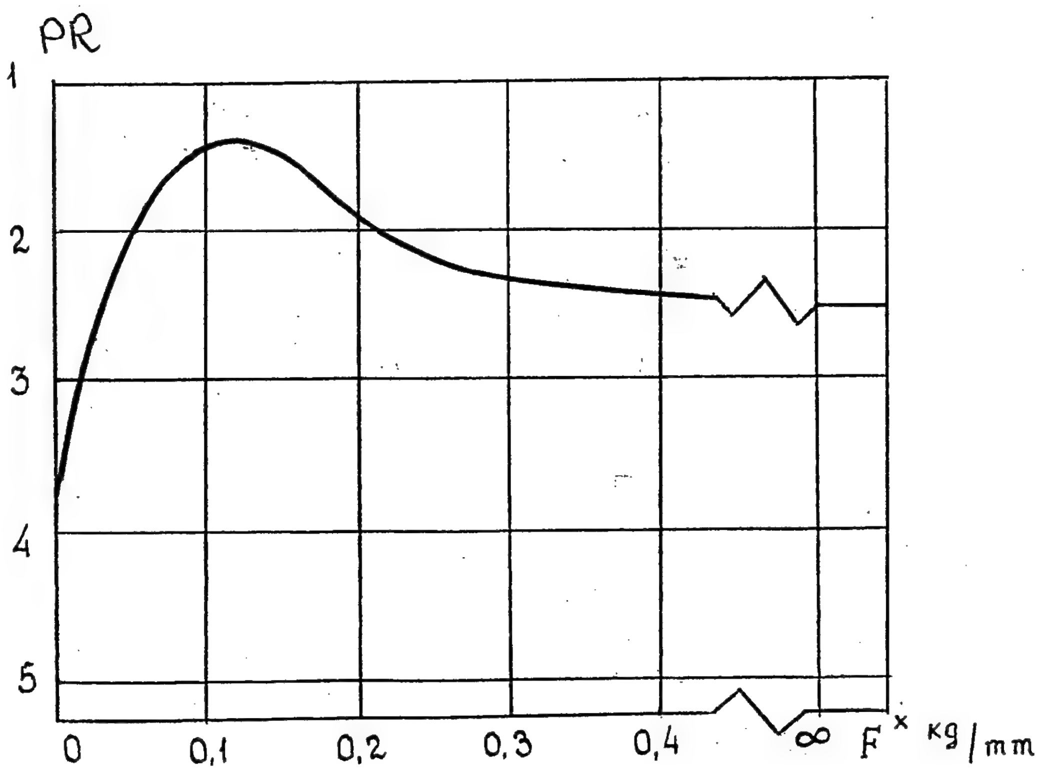


Fig.3.14. Influence of the side stick loading gradient on the pilot rating.

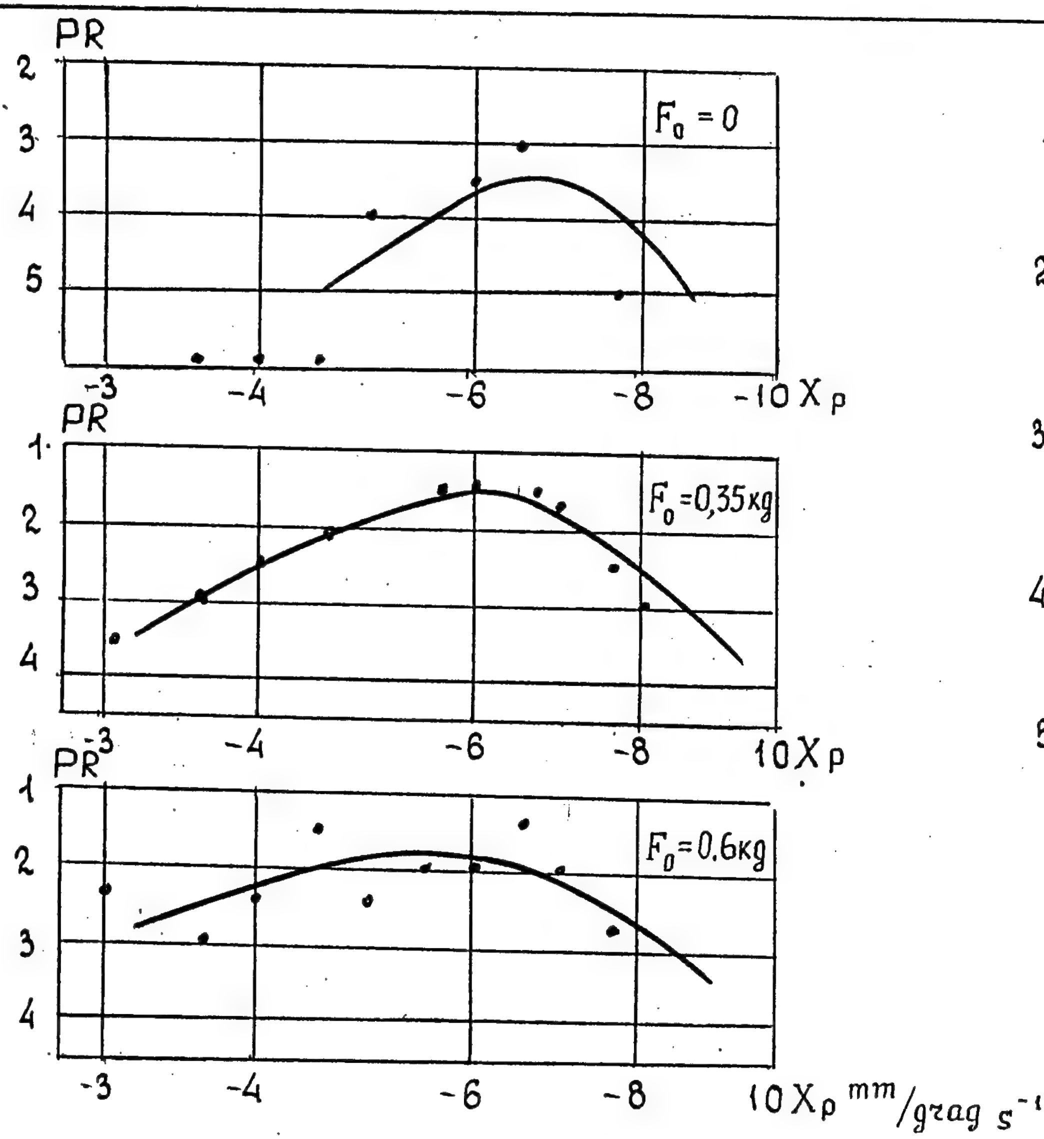


Fig.3.15. Influence of the lateral control sensitivity and breakout on the pilot ratings.

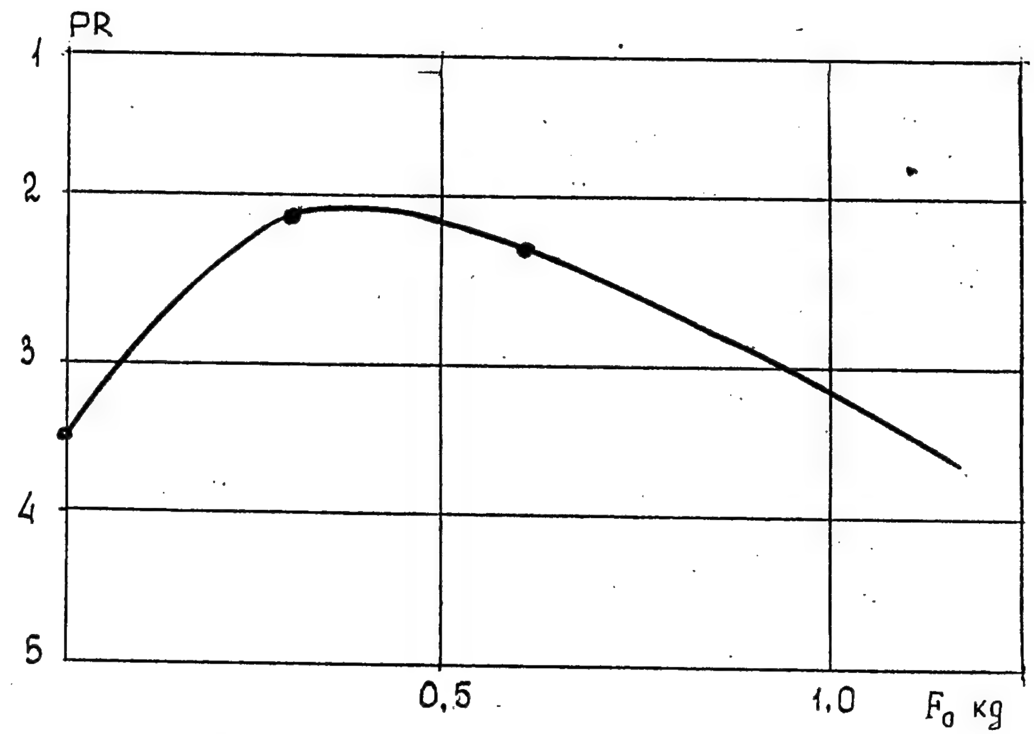


Fig.3.16. Influence of the breakout on the pilot ratings.

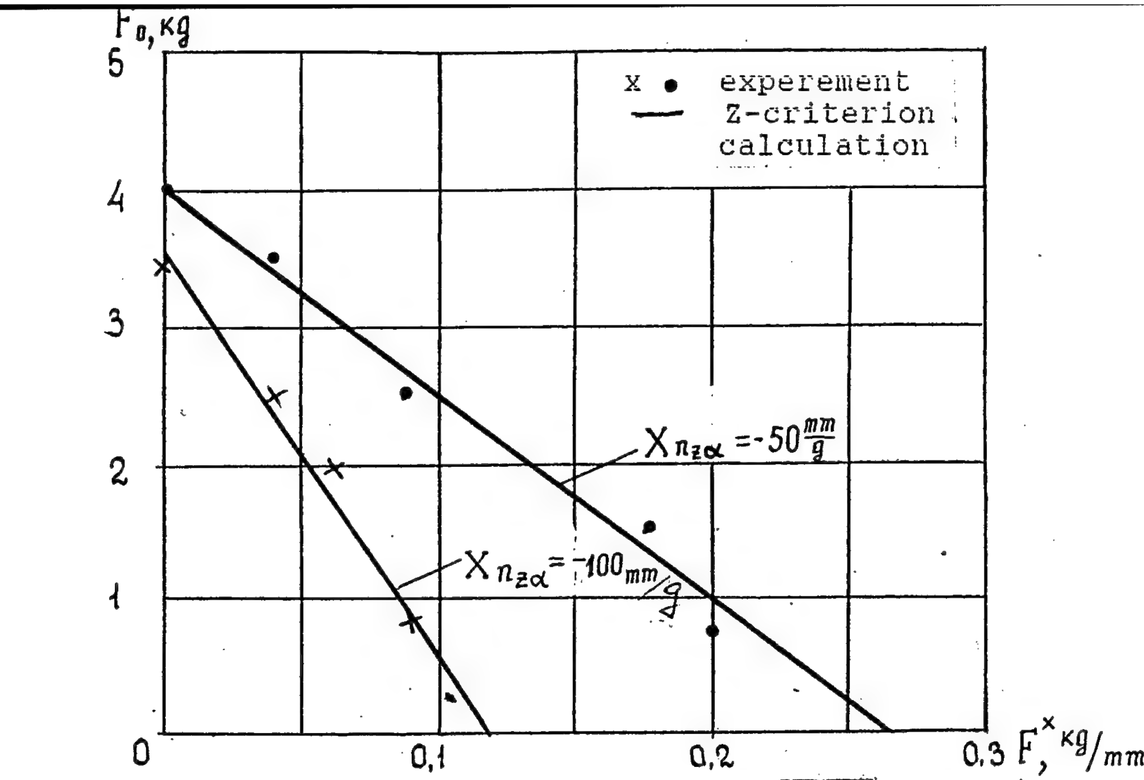


Fig.3.17. Influence of the loading gradient on the side stick breakout force optimum values.

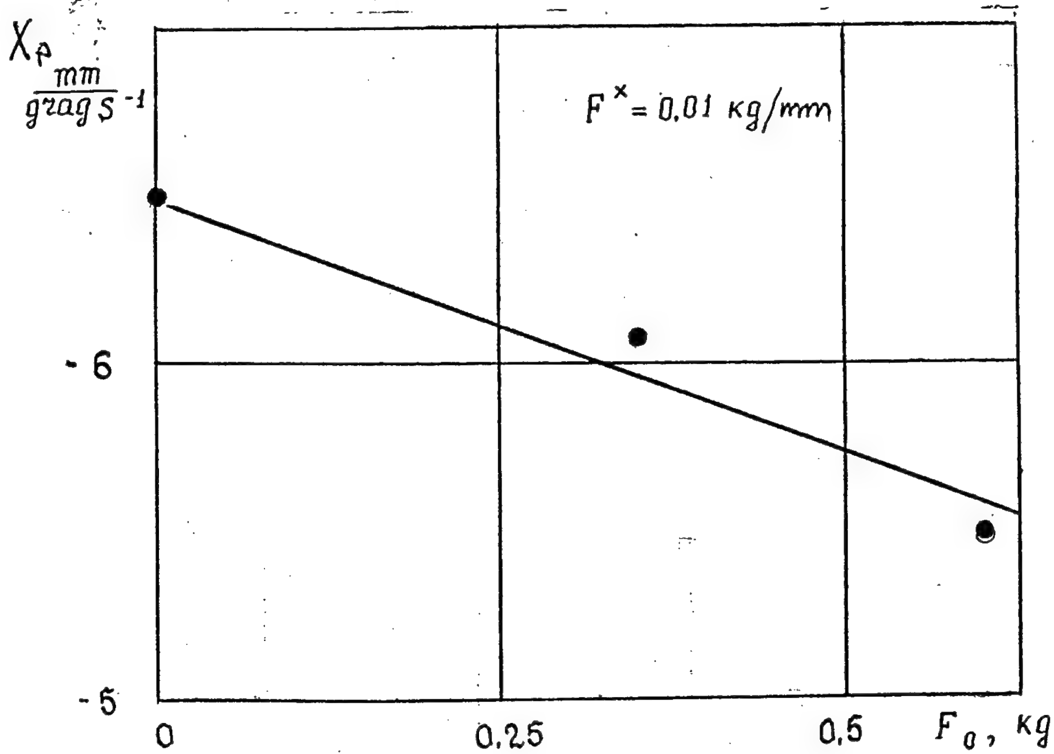


Fig.3.18. Influence of the breakout force on the aircraft control sensitivity

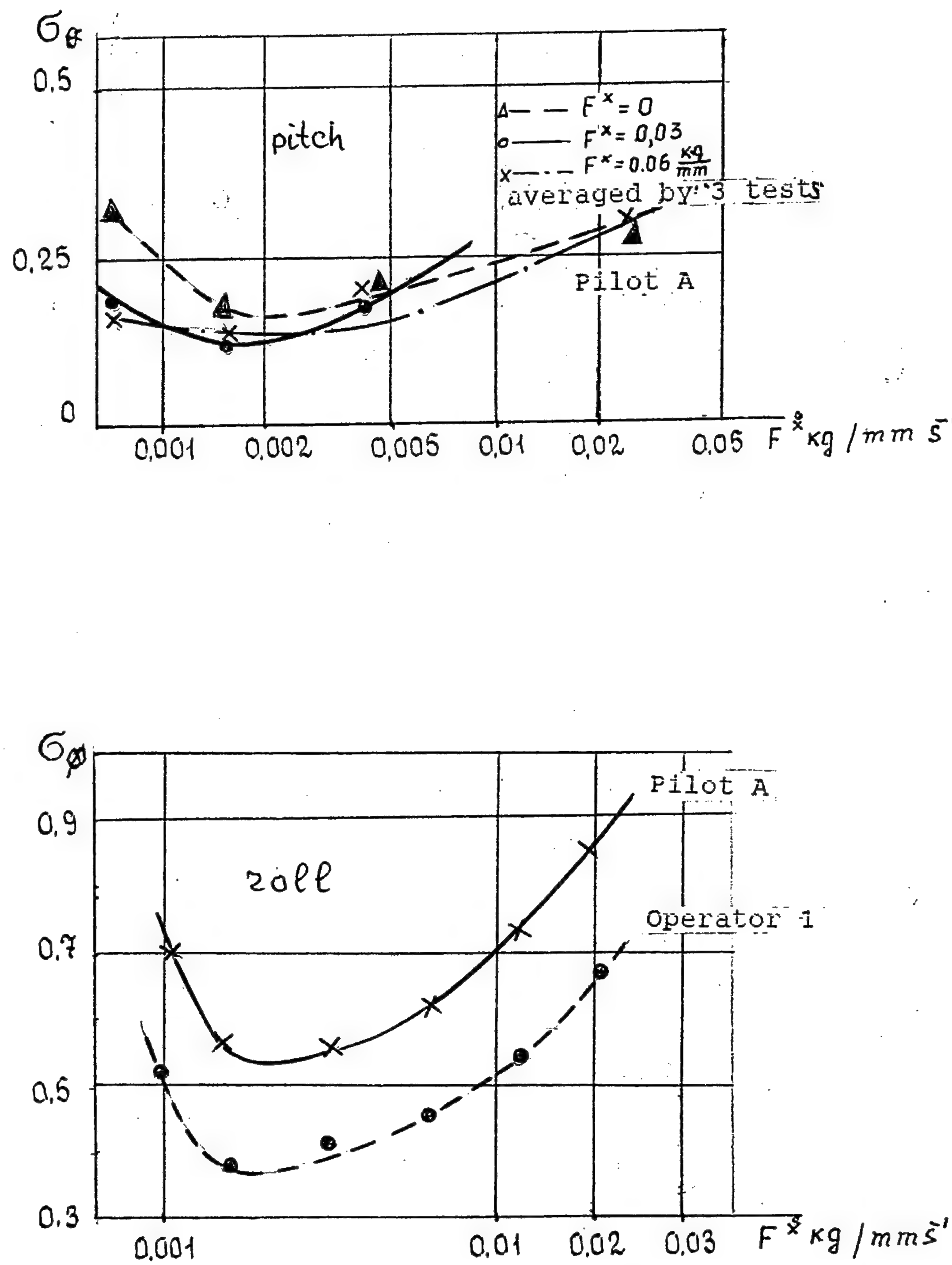


Fig.3.19. Influence of the side stick damping on the pitch stabilization accuracy.

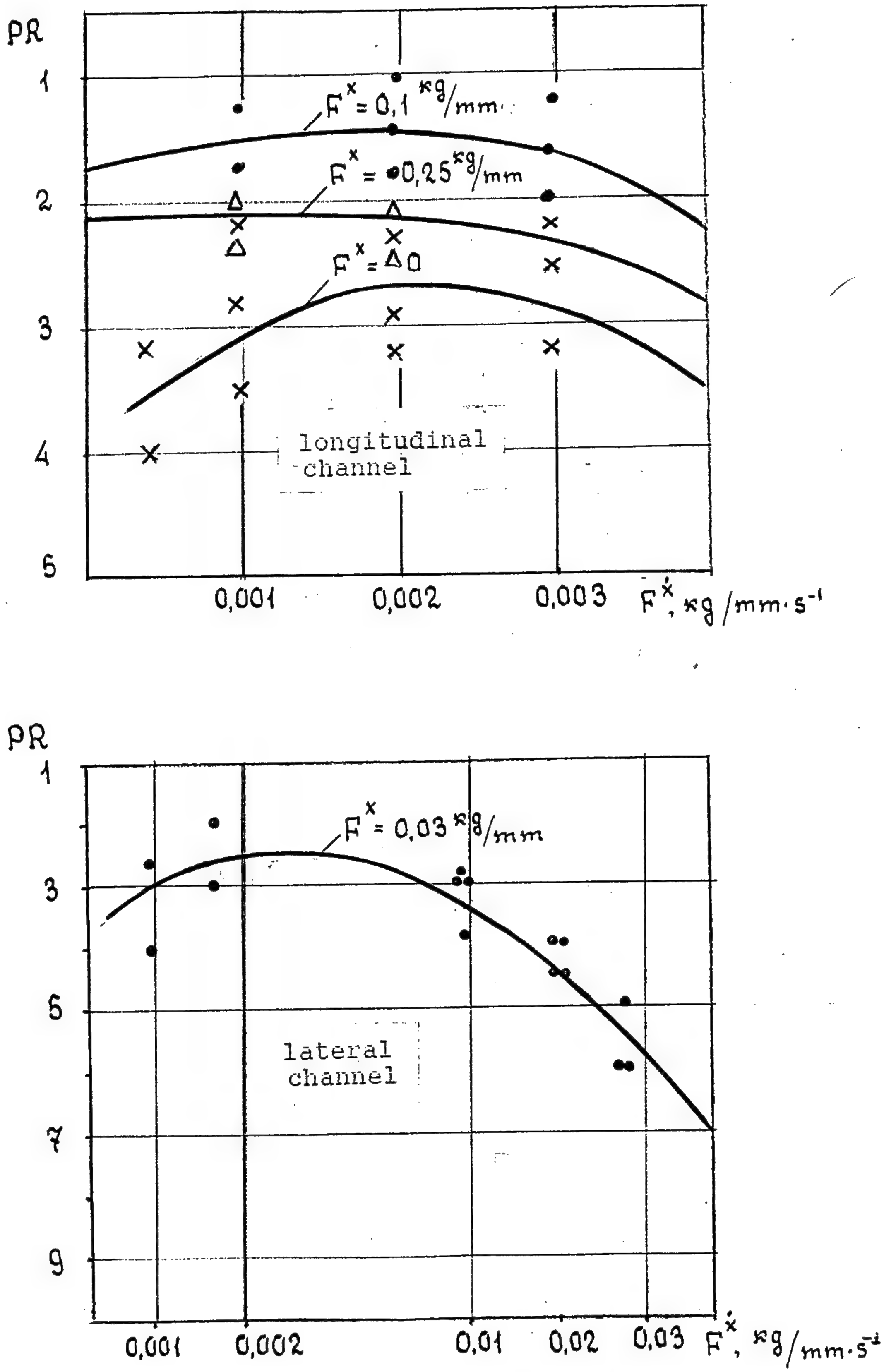


Fig.3.20. Influence of the side stick damping on the pilot ratings.

Dependence of parameter A from side stick loading gradient.

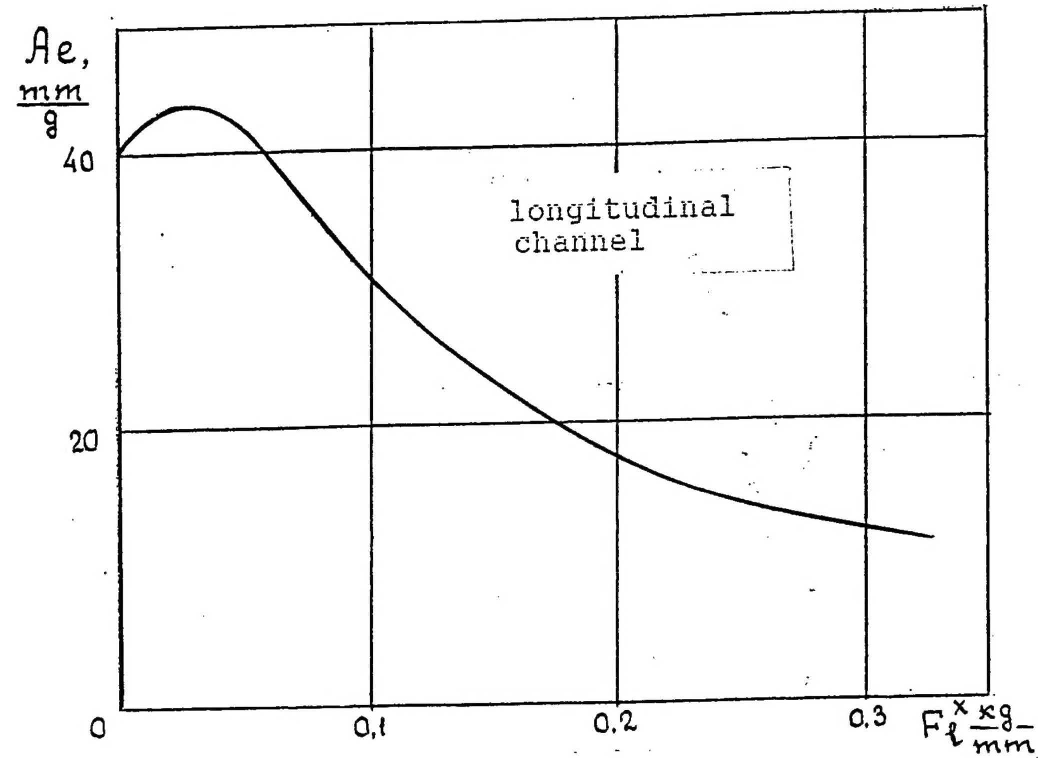


Fig.3.21

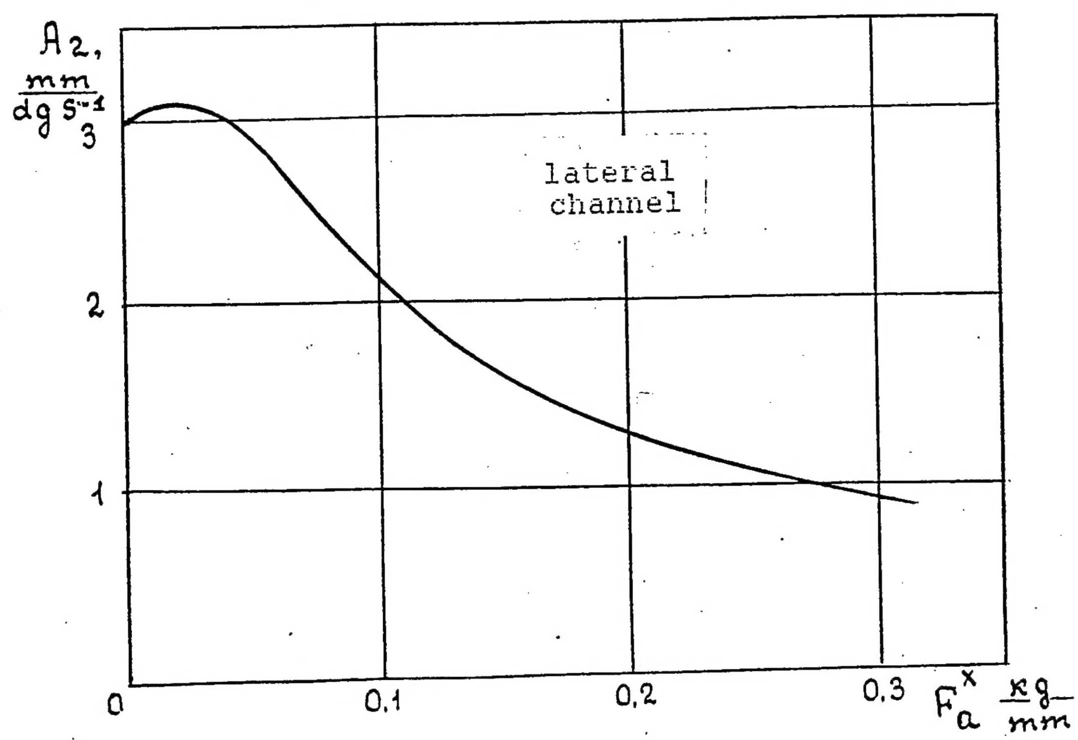


Fig.3.22

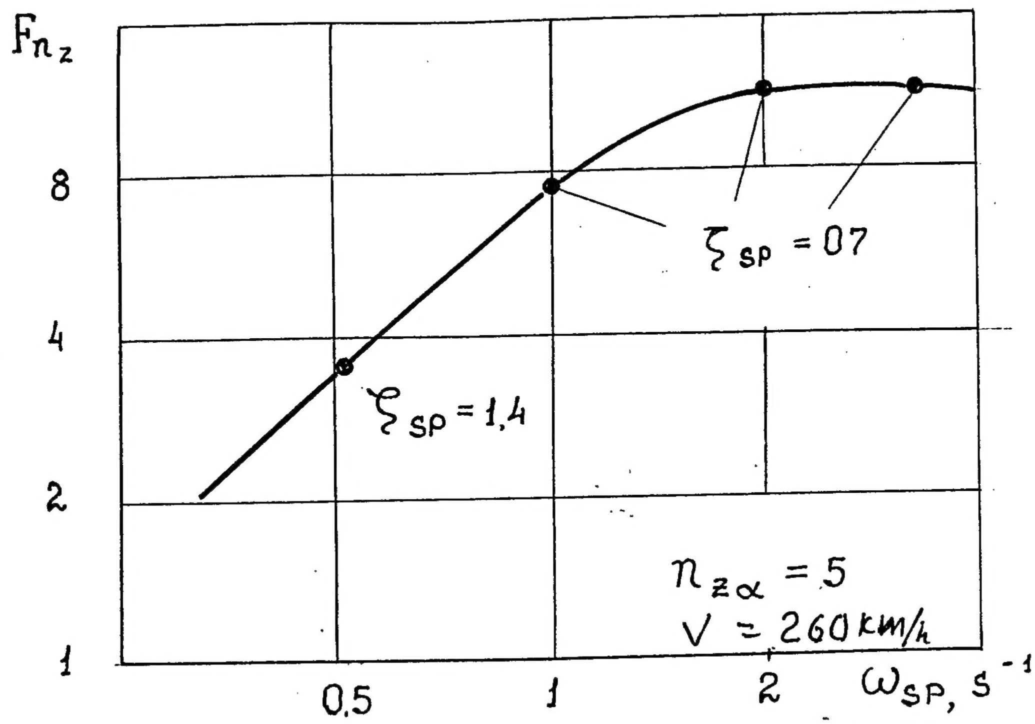


Fig.3.23. Influence of the longitudinal short-period motion frequency w_{sp} on the optimum F_{n_z} values.

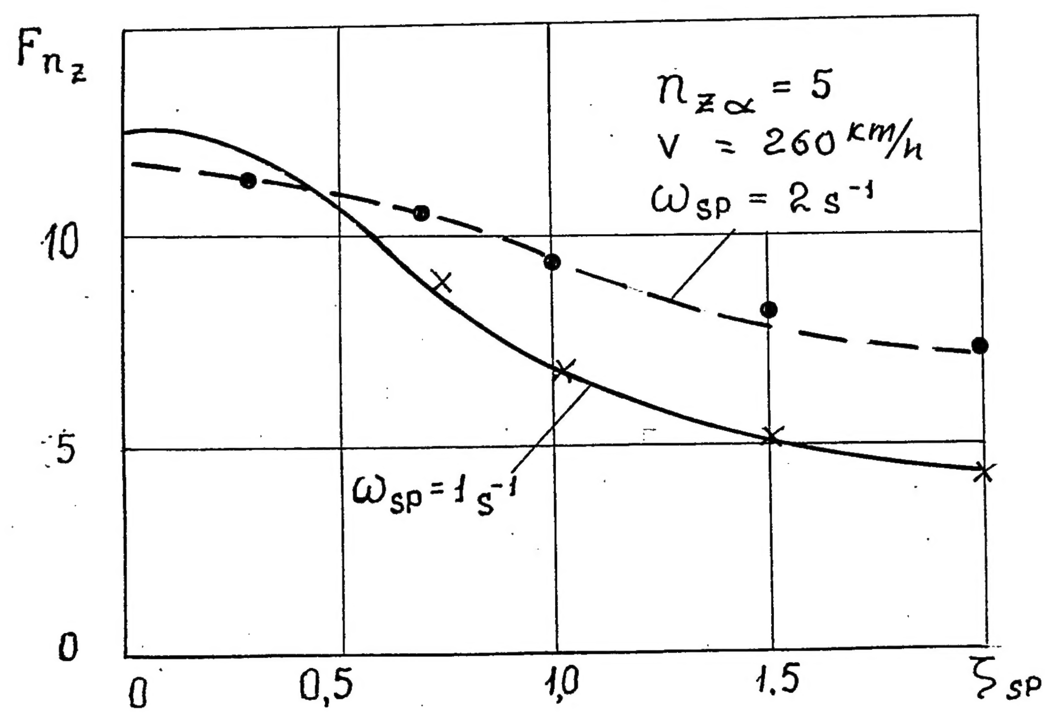


Fig.3.24. Influence of the longitudinal short-period motion damping ζ_{sp} on the optimum F_{n_z} values .

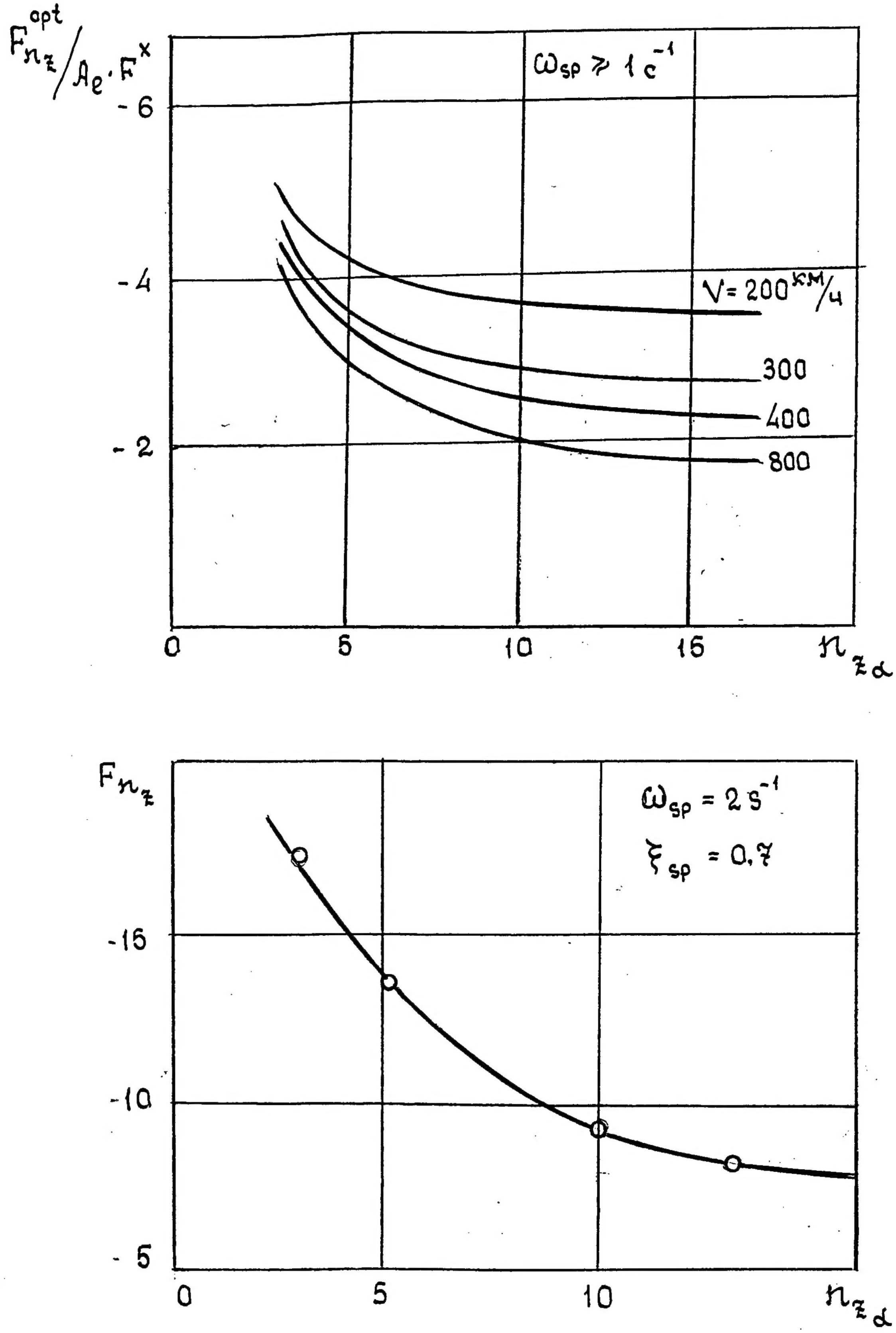


Fig.3.25. Dependence of the optimum F_{nz} values from $n_{nz\alpha}$ parameter.

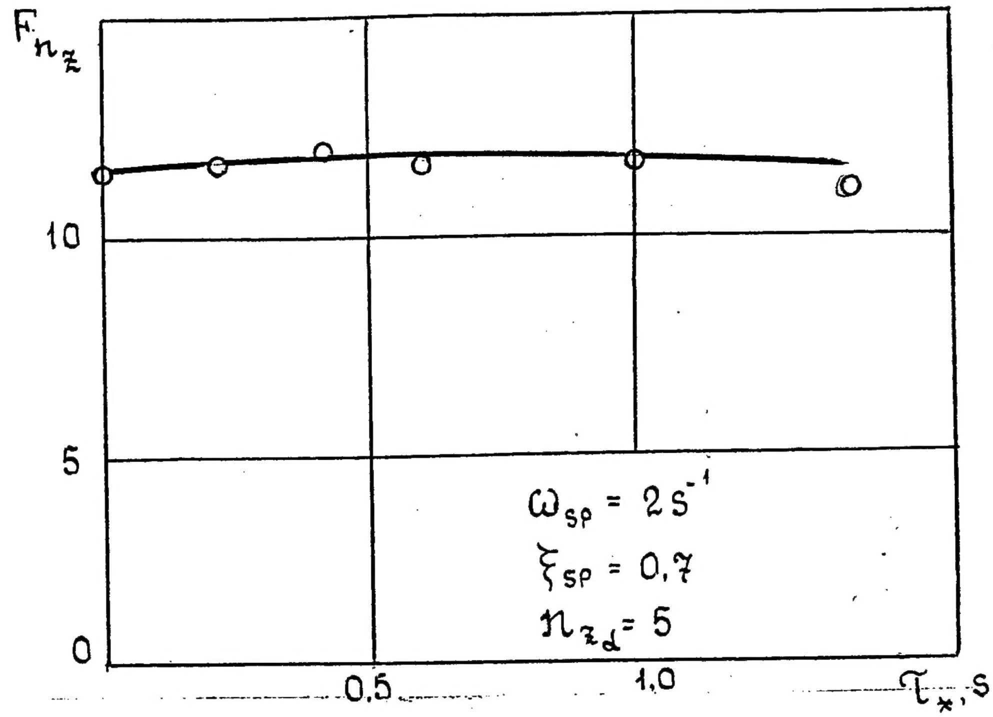


Fig.3.26. Dependence of the optimum F_{n_z} values from time delay.

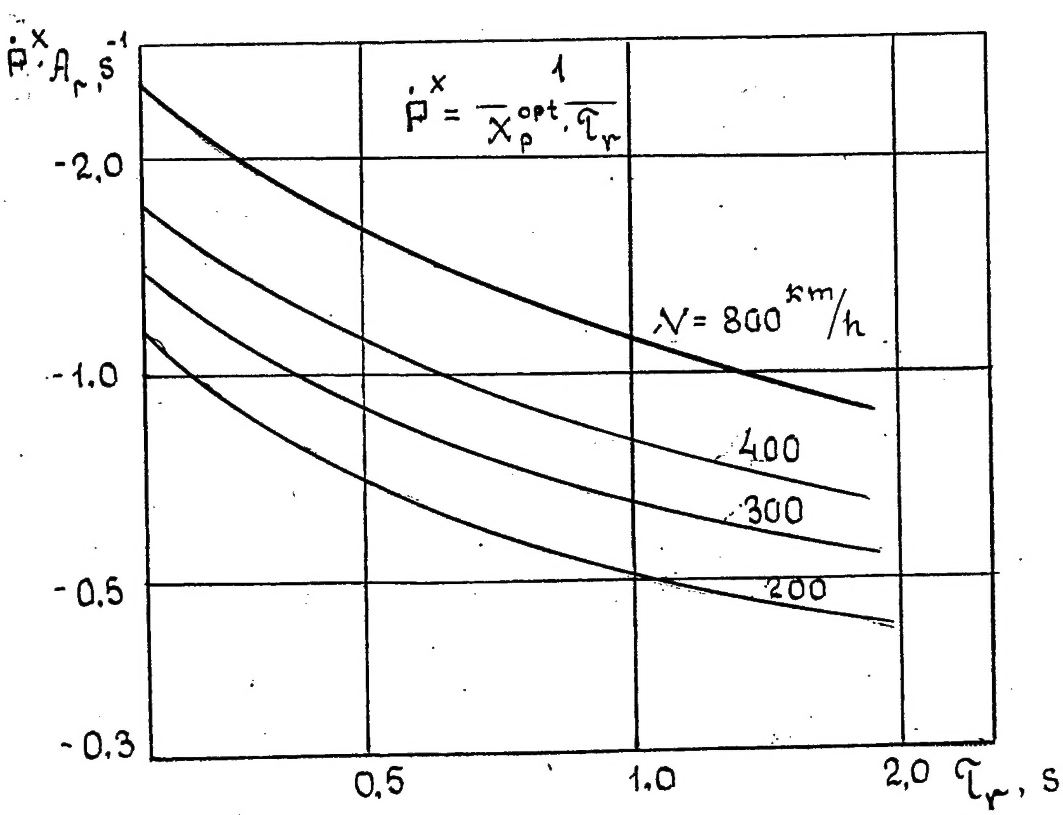


Fig.3.27. Dependence of the optimum $\dot{P}^x$ value from roll time constant τ_r.